NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2701

A SURVEY OF THE AIRCRAFT-NOISE PROBLEM WITH SPECIAL REFERENCE TO ITS PHYSICAL ASPECTS

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CONTENTS

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SUMMARY

This brief survey is aimed at providing a background for various general phases of the aircraft-noise problem. Material has been drawn from National Advisory Committee for Aeronautics noise-research programs at the Langley Laboratory, from visits to various organizations which are concerned in some way with the aircraft-noise problem, and from a review of the literature. The effects of noise are discussed briefly as a background for the reader and brief discussions of the physical characteristics of aircraft noise and some ways of protection from noise are also included along with a limited bibliography of research work applying to the aircraft-noise problem.

These and other related studies indicate that no easy and inexpensive solution to the aircraft-noise problem is available at present. Reductions of noise at the source are possible in some cases, as for the propeller and the reciprocating engine, but only if a possible performance penalty is acceptable. The problem of providing adequate protection is in many cases expensive and is complicated by the intense low-frequency content of the noise from most aircraft-noise sources.

INTRODUCTION

The problem of aircraft noise and its reduction has been of interest for many years but is becoming of greater concern because of the higher noise levels being generated and the ever increasing number of people being affected. Developments of more powerful propulsion systems for military and commercial use have inherently resulted in higher noise levels. Thus not only are passengers, crews, and service personnel of airplanes affected to a greater degree, but so are larger groups of people working and living near airports and test facilities. Because of the widespread interest in this subject and because of its importance, the National Advisory Committee for Aeronautics, other governmental agencies, and aircraft companies are continuing their basic research relative to aircraft-noise problems in general, in an attempt to define the present and future scope of the problem and to explore the possibilities of their solution.

In the present paper information of specific application to the aircraft-noise problem and, in addition, information of a general nature which has a bearing on this problem has been collected for purposes of a brief survey. Because of the complexity and the many ramifications of the aircraft-noise problem, only the more important results on some of its phases are included. Material for this paper has been drawn from noise-research programs at the Langley Laboratory, from visits to various organizations which are concerned in some way with the aircraft-noise problem, and from a review of the literature. An attempt has been made to acknowledge the available sources of material where possible and the references of the present paper constitute a limited bibliography of significant research work which applies to the aircraft-noise problem. The reader may obtain more detailed information from the references listed, some of which are digests of many other references and hence are themselves surveys of certain phases of the problem.

The paper first deals with the effects of noise as a background for the reader and as a basis for discussion of the other material. Next in order of presentation is a description of the physical characteristics of aircraft noise, and finally some ways of protection from noise are discussed.

EFFECTS OF NOISE

The effects of noise on man are complex since both objective and subjective reactions may be experienced simultaneously. Of these, the latter are much more difficult to evaluate since they vary widely from person to person and may be affected by many other factors. The reaction of any given person may vary according to the activity in which he is engaged and according to his personal or business relationship to the noise-producing agency. For instance, if he were a neighbor he might be less tolerant of the noise than if he were exposed to it in the course of his regular duties. His reactions might be still different if he were a paying passenger on an airline.

Acceptable noise levels will be different for various activities and will vary with the individual and with the quality of the noise. Although no attempt is made in this paper to establish noise criteria for subjective phenomena, some physiological and psychological effects of the noise are described. Since many inconclusive results are found in the literature in regard to psychological reactions, only the results of a general nature from a large number of these studies are summarized (ref. 1).

(Sound-pressure levels discussed in this paper are expressed in decibels and, as is conventional, are measured relative to a reference pressure level of 0.0002 dyne/cm^2. The sound-pressure level in decibels is thus equal to $20 \log_{10} p/0.0002$, where p is the sound pressure in dynes/cm^2. As is well-known, the ear responds to a wide range of pressure levels. For illustration, the pressure amplitudes of normal conversational speech may be a fraction of 1 dyne/cm^2 (50 to 70 decibels); whereas, a pressure amplitude of 200 dynes/cm^2 (120 decibels) usually causes discomfort to the observer.

(Some of the relationships for sound-pressure variations are expressed as power functions; the exponent for the power function of the sound energy is twice that for the sound pressure.)

Annoyance

The annoyance caused by a steady noise is a function of its intensity level and frequency spectrum. Annoyance increases as the intensity increases and is generally greater for noises containing the higher frequencies than for those of predominantly low frequency. Other factors known to increase the annoyance are unexpectedness, inappropriateness, and intermittency.

Work Output and Efficiency

Short exposures of individual workmen to noise levels as high as 120 decibels and long-term exposures to lesser intensities do not seem to affect adversely their performance of most jobs involving mental and muscular work. A workman is thus apparently able to adapt himself to a noisy environment for the purposes of doing certain jobs, although subjective feelings of annoyance are sometimes observed. For certain tasks where concentration is required, the presence of some noise may even be beneficial. It is recognized that adverse auditory effects may be observed by the person exposed, unless adequate protection for the ear is provided. Aside from these possible auditory effects, some of which are discussed subsequently in this paper, there is little evidence that man is affected physiologically by noise levels up to 120 decibels.

For jobs involving talking or listening or where communications are necessary, as in teamwork, noise is detrimental to working efficiency and in some cases may constitute a serious hazard.

Effects on Communication

Because of the ability of noise to mask speech frequencies, it may interrupt all types of communications. The consequences thus may range in severity from annoyance in the case of social conversations to life-and-death matters in vital communications.

The quality of the noise spectrum is significant since its masking action is a function both of intensity and frequency. As an example, the masking action of a 400-cps pure tone with an intensity of 70 decibels is illustrated in figure 1 as a function of frequency (ref. 2). The amount by which the hearing threshold is raised for each frequency is a measure of the masking and is indicated by the curve in figure 1. A small amount of masking was produced at frequencies below the masking frequency; whereas a relatively large amount occurred at frequencies above the masking frequency. The most detrimental effects occurred at frequencies nearly coincident with and slightly above the masking frequency. Although these results are for one particular masking frequency, similar results have been obtained for other frequencies. Noise frequencies below the speech range thus will have some masking action on speech even at relatively low intensities. Noise frequencies above the speech range will have little or no masking effects.

In instances where speech is masked by high-level noise, the use of earplugs will usually improve the intelligibility. This benefit arises because of the nonlinear response of the ear to sounds of various intensities. In general, high-level speech is less intelligible than low-level speech. When earplugs are used, the signal-to-noise ratio is essentially unchanged but the signal strength may be reduced to a value which makes it more intelligible (ref. 1).

Deafening Effects

At levels above approximately 85 decibels, the most common physiological effect of noise on man is the production of hearing losses. The nature and amount of hearing loss produced is a function of the intensity of the noise, its frequency, and the duration of exposure. The complete relations of hearing loss to frequency, intensity, and duration are complex and vary somewhat with the individual. Hence only a few of the more general results in references 1, 3, 4, and 5 are included herein.

A given hearing loss may be incurred by exposure to an intense noise of short duration or by a less intense noise for a longer duration. The greatest hearing losses are generally produced at the predominant noise frequency or in a higher band of frequencies, or both. An exposure to a band of frequencies produces approximately the same hearing loss as a pure tone of the same intensity and of frequency corresponding to the middle of the band. Figure 2 illustrates the temporary hearing loss for an observer after a short exposure to a rather intense jet-engine noise spectrum (ref. 5). The greatest losses in this instance occurred in the range of frequencies most useful for speech perception (500 to 2000 cps).

Hearing loss as well as recovery of hearing usually begins rapidly and then progresses more and more slowly as a function of time. Most of these deafening effects are temporary and normal hearing returns in a period of time ranging from a few hours to several days. Permanent hearing losses may occur only after repeated exposure before recovery is complete.

Effects of Intense Noise

Auditory effects.- In addition to the well-known deafening effects of noise, certain other effects are produced in the audible frequency range (15 to 15,000 cps) at intensities above 120 decibels. This level is generally regarded as the approximate threshold of feeling and may be uncomfortable to the observer. As the noise levels increase above this value, more and more discomfort is experienced until pain occurs at about 140 decibels. Experimental evidence exists which indicates that physical damage to the hearing mechanism such as puncturing of the eardrum may occur at levels of approximately 160 decibels (ref. 6). For noise frequencies in the 2000 to 15,000 cps range, the main effects at all intensity levels are associated with the hearing mechanism.

Nonauditory effects.- At frequencies below 2000 cps various nonauditory effects also appear (refs. 5 and 6). When a person is exposed to noise levels of approximately 150 decibels in the frequency range of 700 to 1500 cps, he may experience resonances of the head bones and cavities as well as blurred vision. At audible frequencies below 700 cps, similar sensations are experienced in the region of the chest and stomach and various muscular groups are affected. Very little information is available for the lower audible and subaudible ranges although noise at these frequencies may also produce significant physiological effects.

In laboratory tests, small furred animals have been killed by overheating due to absorbed sound energy at audible and ultrasonic frequencies (ref. 7). The ability of the animal to absorb this energy is indicated qualitatively as a function of frequency in figure 3, along with similar data for man (ref. 8). As indicated in the figure, as the noise frequency increases, the animal is generally able to absorb the energy more efficiently; whereas the reverse is true for man. These same general trends are believed to apply into the ultrasonic frequency range.

Results such as indicated in figure 3, together with the knowledge that the ultrasonic noise components in aircraft-noise spectrums are relatively low in intensity, have led to the conclusion that there are at present no serious hazards to man in the ultrasonic frequency range.

Fatigue of Structures

In the oscillating pressure field surrounding a noise source the intensity depends on the distance from the source. At some distance away these oscillating pressures are recognized only as noise and may produce some of the effects on man that have already been discussed. At points very close to the source, they produce more intense noise and may also be capable of exciting destructive vibrations in nearby parts of the aircraft structure. Studies of these intense oscillating pressure fields and their associated vibrations are of interest in connection with the fatigue problem.

Many failures of the secondary structure of wings and fuselages have been observed in propeller and jet aircraft due to accelerated fatigue. In propeller airplanes (ref. 9) these failures have occurred generally in the fuselage near the propeller plane of rotation and in the trailing-edge wing structure for pusher configurations. In jet airplanes, failures of the tailpipe, fuselage, and wing secondary structures near the jet exit have been observed. An increase in clearance between the noise source and the structure affected is usually beneficial in alleviating this condition. For existing configurations, changes in the rigidity, mass, and damping of the structure may be a satisfactory solution.

PHYSICAL CHARACTERISTICS OF AIRCRAFT NOISE

The material in this section relative to the physical characteristics of aircraft noise is applicable specifically to the condition of zero forward speed unless otherwise noted. Information for the static case, however, may also be applied approximately to conditions of low forward speed, as in take-off and climb. Low-altitude and static operations of aircraft are known to bring about most of the noise problems. In normal flight, noise will generally be a serious consideration only for occupants of the aircraft, and for this condition the effects of forward speed, especially in the high-subsonic range and above, are not well-known.

Characteristics of various aircraft-noise sources such as propellers, jets, and rockets are considered. Frequency spectrums, directional characteristics, and intensity levels are presented, and provision is made for a comparison of the noise from some of the various units considered.

Frequency Spectrums

Figures 4, 5, and 6 show schematically three general types of sources of aircraft noise, namely, propellers, pulsing flows, and turbulence and jet mixing. The frequency spectrums and associated wave forms in the figures were recorded photographically from the viewing screens of a Panoramic Sonic Analyzer and a cathode-ray oscillograph, respectively.

Steady forces varying in distance.- One basic type of noise is generated by propellers and is illustrated in figure 4. The rotational noise, which is the main component of propeller noise, is generated by a constant aerodynamic force on the blade which, as a cyclic function of time, varies in distance to the observer. Typical noise spectrums for a propeller operating at subsonic and supersonic tip speeds (ref. 10) are shown in the figure where intensity appears as a function of frequency. The noise consists primarily of a few frequencies of constant amplitude which are harmonically related to the blade-passage frequency. It is significant that at supersonic tip speeds (fig. 4(b)) some of the higher-order harmonics are more intense than the fundamental, with the result that the characteristic wave form is very sharply peaked, as indicated by the typical pressure time-history record shown at the right-hand side of the figure. At the subsonic tip speeds (fig. 4(a)), the spectrum generally contains less harmonic content and the over-all intensities are lower. In general the more intense noise frequencies from either type of propeller will appear in the spectrum below 1500 cps.

Pulsing flow.- A pulse-jet engine, which is designed to operate in a cyclic manner, is a pulsing-flow-noise source. The exhaust gases are expelled periodically at a frequency which is a function of the engine configuration and its operating temperature. Noise from an engine of this type is illustrated schematically in figure 5. The spectrum associated with this type of source is shown in the left-hand side of the figure and is seen to contain only a few discrete frequencies, the fundamental or firing frequency being the predominant one. The wave form shown in the right-hand side of the figure is associated with a spectrum of this type and is indicative of its low-frequency content.

Another common pulsing-flow-noise source is the reciprocating-engine exhaust. Exhaust noise spectrums indicate that the most intense noise component usually corresponds to the fundamental firing frequency of the engine and all other components are of lesser intensity. Thus the spectrum from this type of pulsing-flow source may be similar to that of figure 5 except for some possible subharmonics which are believed to be caused by dissimilarities in the manifold system and for some high-frequency noise of an aerodynamic origin.

Even though the results in figure 5 apply directly to the pulse-jet engine, similar discrete frequency spectrums have been obtained for ram jets and for a turbojet with afterburner. Thus the noise generated by pulsing-flow phenomena is believed to be closely related to that generated by rough burning or to possible resonances which may occur during operation of continuous-type engines, or to both. Very little information is available concerning these phenomena since they are avoided whenever possible because of intense noise and vibration.

Turbulence and jet mixing.- The next noise source to be considered is the mixing region of a jet issuing from a chamber into the atmosphere as shown schematically in figure 6, along with a typical spectrum and wave form. The mechanism of this type of noise generation is not well-understood but experiments have shown that a smooth flowing jet of air issuing into the atmosphere is an intense noise source. The mixing region of the jet is of interest because it is one of the main sources of noise from the turbojet engine. The noise is apparently associated with turbulence and a typical spectrum contains nearly all frequencies from the subaudible to the ultrasonic range (ref. 11). Since so many frequencies are present and in random phase, the resulting over-all signal presents a hashy picture as a function of time on the viewing screen of a cathode-ray oscillograph. This result is in marked contrast to the steady characteristic wave form of the propeller in figure 4. The distribution of energy in the sound spectrum of jets has been found to be a function of the jet size; however, for jet engines in current use the peak intensities will probably occur at frequencies near 1500 cps or below.

Directional Characteristics

The radiation patterns of the over-all noise from some propulsive devices are highly directional in nature and thus may affect the ground-handling of aircraft and even their design and operation. An indication of some of these directional characteristics is given in figure 7, which is a polar diagram showing the relative over-all pressure amplitude as a function of azimuth angle from the thrust axis (0° in front) for a turbojet engine, a propeller (ref. 10), and a reciprocating-engine exhaust (ref. 12). Propeller noise is a maximum near the plane of the propeller where the distance variation between the observer and the propeller blade is greatest. Jet noise is a maximum to the rear of the orifice near the jet boundary (see ref. 13), and the azimuth angle at which the maximum occurs is dependent in part on the sound-propagation velocity of the jet medium. As the sound-propogation velocity increases, an apparent refraction effect causes the maximum value to move outward from the jet boundary. There is no experimental evidence to indicate that the maximum values will occur at azimuth angles, as defined in figure 7, appreciably less than 135°. Measurements of the over-all noise for pulsing-flow sources indicate that the radiation patterns are only slightly directional, as indicated by the data for the reciprocating engine in figure 7.

Variations in the frequency content of the noise as well as its intensity level may occur as a function of the observer's azimuth angle. For jets a greater proportion of low-frequency noise is observed near the jet boundary; whereas at positions perpendicular to the jet axis the higher frequencies become relatively more intense. Propeller-noise frequencies are a function of the rotational speed of the propeller except at azimuth angles very close to the thrust axis where the noise associated with shedding of vortices from the blades is most intense. This vortex noise is random in nature and is usually of higher frequency than the rotational component. For propellers operating at low tip speeds, as in references 14 and 15, the vortex-noise component may be a relatively large part of the total noise. Since its intensity increases at a slower rate as a function of tip Mach number than does the rotational component, it is a relatively unimportant part of the over-all noise at high tip Mach numbers.

Over-All Intensity Levels

Propellers.- For a given disk power loading the over-all propeller noise may be a function of the tip Mach number, the number of blades, and the blade geometry. Figure 8 shows the relative over-all sound intensity as a function of tip Mach number for a two- and a six-blade propeller for constant power input (refs. 9, 10, and 14 to 19). It can be seen that a decrease in the sound intensity can be achieved by using more propeller blades; however, the decrease obtainable is greater at the lower tip speeds than at the higher ones. For both propellers the tip Mach number is a significant parameter in the subsonic range; whereas, in the supersonic range, the sound intensity is essentially independent of the tip Mach number. At subsonic tip Mach numbers, large sound reductions can be obtained by increasing the number of blades and reducing the tip Mach number. At supersonic tip Mach numbers a relatively small benefit would be obtained from this technique. Some preliminary tests have shown that blade plan form which apparently is not significant at subsonic tip Mach numbers may be a significant parameter in the supersonic range. The wider blades may cause some reduction in intensities, particularly for the higher harmonics.

It has been demonstrated that quiet propellers are technically feasible for small personal-owner-type airplanes by the tests of references 14 and 15. It is believed that the same principles may be applied to the quieting of propellers of transport-type airplanes although large design and development problems and costs would probably be encountered. Some of the factors which must be considered in the design of quiet propellers are outlined in reference 20.

Reciprocating engines.- The main source of noise from the reciprocating engine is the exhaust. The intensity varies as a function of the type of manifold system used and in some instances may be of the same order of magnitude as the propeller noise. The exhaust noise increases in amplitude at a slower rate as a function of engine rotational speed than does the propeller noise (ref. 21). The latter then is usually most intense in present-day aircraft for take-off, climb, and cruise conditions (ref. 4), although in some instances the exhaust noise may be more objectionable. When some provision has been made to quiet the propeller, as in references 14 and 15, the exhaust noise must also be reduced in order to achieve effective over-all noise reduction. If stub exhausts are used for reasons of performance, the exhaust noise levels may be somewhat higher than if the collector-ring type of manifold is used.

Turbojets.- From current tests it has been found that turbojet engines are very closely related to simple air jets in regard to their noise generation. It was also found that jet noise increased in intensity as the jet velocity and exit gas density and turbulence increased. The predominant parameter affecting the noise intensity is the jet exit velocity and is shown in figure 9, where sound pressure is plotted as a function of jet exit gas velocity. The sound pressure is thus seen to be a power function of the velocity, with the exponent of the power being slightly larger than 3.0. Thus if the velocity was varied by a factor of 2, the sound pressures would be varied by a factor of approximately 10. This figure indicates that a trend toward higher engine operating temperatures with their higher associated jet velocities will mean correspondingly higher noise levels.

Afterburner units.- Figure 10, where over-all noise levels are shown as a function of the observer's azimuth angle, shows a comparison of the noise generated by a turbojet engine with and without afterburner. Both sets of data were recorded at the same distance from the source and are adjusted to the same thrust rating for comparison. The directional characteristics are seen to be similar in each case, but the noise levels associated with afterburner operation are higher at all azimuth angles. This increase in the noise level is due in part to the higher exit gas velocities of the afterburner unit. The results in figure 10 are for one particular engine, and since the data may be affected by the degree of rough burning, these results may not be characteristic of afterburners in general.

Turbopropeller units.- Noise measurements are not available for turbopropeller units; however, some estimates of the noise levels for two different units have been made and the results are shown in figure 11. Intensity levels are plotted as a function of azimuth angle for conditions of 5000 pounds of thrust and a distance of 300 feet. For the purposes of this comparison the assumption has been made that the propeller provides 90 percent of the thrust and that the jet provides 10 percent of the thrust while operating at a tailpipe temperature of approximately 1400° F abs.

The subsonic-turbopropeller (tip Mach number of 0.9) curve has been estimated from the two dashed curves shown in the figure which show the contribution to the over-all noise of the jet exhaust and the propeller. At the given conditions, the propeller is the main contributor, although at some azimuth angles the jet-exhaust noise may be of the same order of magnitude. In the case of a supersonic-type turbopropeller, the propeller is clearly the dominant noise source at all azimuth angles.

Rockets.- In general, the noise generated by rocket engines appears to be very similar to the noise from turbojets in regard to frequency spectrums and radiation patterns. Figure 12 shows the over-all noise levels generated by two types of solid-fuel rocket engines as a function of the azimuth angle. All data have been adjusted to a distance of 300 feet and a thrust rating of 5000 pounds. The curve for smooth burning represents data for a thrust-augmentation type of rocket engine, whereas the curve for rough burning was obtained from tests of a larger engine used to propel missiles. The differences in levels for these two curves may represent the difference between smooth and rough burning for this type of engine.

Pulse jets.- The pulse-jet engine is a prolific generator of low-frequency noise. The spectrum, as shown in figure 5, consists primarily of a few discrete frequencies of which the fundamental or firing frequency is the most intense. Measurements for an engine rated at 90 pounds of thrust indicated that the radiation pattern was only slightly directional in the region to the rear of the engine and the intensity levels at a distance of 10 feet were greater than 140 decibels.

Ram jets.- Data for a small subsonic ram-jet unit of the type used to propel helicopter blades indicated that the quality of the noise was very similar to that shown in figure 5 in that several discrete frequency components were present in addition to the characteristic random noise of continuous-type jets. Measurements on larger engines have given similar results, and this type of spectrum is believed to be generally associated with ram-jet engines. Tests showed the noise in the frequency range of 0 to 40 cps to be sharply directional, with the maximum near the jet axis to the rear of the engine. Noise in the frequency range of 40 to 15,000 cps seemed to be only slightly directional, with the maximum also near the jet axis.

Aerodynamic noise.- Aerodynamic noise is generated in the boundary layer of the airplane as it moves through the air. It is associated with turbulence and has a spectrum similar to that in figure 6. In one instance a noise level of approximately 130 decibels was recorded in the cockpit of a fighter airplane at an indicated airspeed of 500 mph; hence this type of noise may predominate in the cockpit and passenger compartments of some jet aircraft. This noise will probably not be of concern to observers outside the airplane since it is an important consideration only at high flight speeds.

Data on the aerodynamic noise in the passenger compartment of a large glider are shown in figure 13 where sound pressures are plotted as a function of air velocity (ref. 22). The sound pressures are seen to be a power function of the air velocity with the exponent being approximately 2.3. Data obtained in various types of aircraft by Rogers and other investigators indicate that this exponent applies approximately throughout the subsonic flight range for a variety of aerodynamic shapes. The intensity level may be higher for poor aerodynamic shapes and will vary in accordance with the sound-transmission characteristics of the fuselage wall. It was also noted that the energy in the spectrum apparently tends to shift to the higher frequencies as the air velocity increases. For velocities in excess of 400 mph the peak frequencies will probably occur in the frequency range of 1200 to 2400 cps or higher.

Conventional methods of soundproofing will probably be adequate for protection from this type of noise since the bulk of the sound energy, at the higher flight speeds, appears to be in the frequency range where soundproofing is effective. It is particularly important to have adequate seals around windows, doors, canopies, and so forth, since faults of this type which allow air flow into the airplane may markedly increase the noise level. Pressurized cabins are especially effective in minimizing aerodynamic noise since all leaks are effectively sealed.

Comparison of Noise from Various Propulsive Units

It is of interest to compare the maximum noise levels from various propulsive devices. For this purpose figure 14 has been prepared to include those units for which data are available. All values have been adjusted to correspond to a distance of 300 feet and a thrust rating of 5000 pounds.

The best estimate obtainable of the exhaust noise level for a reciprocating engine is considerably lower than the propeller noise; thus a reduction of the exhaust noise without also reducing propeller noise will result in a relatively small noise reduction. If substantial reductions are to be made in the noise from present-day propeller-driven aircraft, both the propeller and exhaust noise must be reduced.

It is apparent that the noise levels associated with such high-performance units as the supersonic-type propeller, the afterburner, and the rocket engine are higher than for our present-day propulsive devices. Consequently their use will aggravate the noise problem in neighborhoods where there are low-flying airplanes and ground-testing of engines.

PROTECTION FROM NOISE

The fact that some aircraft noise levels are so high indicates that some form of protection should be provided for persons who are exposed to the noise in the course of their duties. Protection is particularly necessary for those who are required to work close to the noise source where the levels may be sufficiently intense to affect them physiologically.

The most desirable method of amelioration is to reduce the noise itself to an acceptable level at the source; however, because of performance considerations or the high noise levels inherent in aircraft propulsion systems, or both, this condition is difficult to realize. The present section briefly describes muffling of jet and reciprocating engines and discusses other means of protection in the cases where reduction of noise at the source is not feasible.

Exhaust Muffling

Reciprocating engines.- For any given reciprocating engine the exhaust muffler can be used as a means of reducing the exhaust noise. Mufflers are usually designed for a particular type of engine since such variables as engine firing frequency, volume of gas flow, and the desired attenuation characteristics are important factors in the design (refs. 12 and 23).

For effective muffling the use of a collector ring is generally advantageous since all cylinders have a common exhaust exit. This configuration will accomplish some noise reduction in itself and will allow the use of one muffler per engine. Since the engine back pressure should be kept at a minimum the mufflers which allow a straight-through passage of the exhaust gases are desirable for aircraft. These mufflers are known as the resonant-chamber type and their acoustic properties are dependent in part on the chamber volumes involved. In general this type of muffler requires larger chamber volumes to attenuate the lower frequencies; hence it is advantageous from the standpoint of muffling for the engine firing frequencies to be as high as possible.

Figure 15, in which intensity is plotted as a function of frequency, shows the composition of the exhaust spectrum from a 190-horsepower reciprocating engine both before and after muffling. The very simple muffler used for these tests is also shown schematically in the figure and its effectiveness is indicated as the space between the curves. Judging from the quality of the spectrum, the task of reducing the over-all noise is apparently one of reducing the low-frequency components since they are of greatest strength. Some difference of opinion exists as to which frequencies need the greatest reduction since some observers believe that the higher ones are more objectionable. This particular muffler design is capable of providing some noise reduction throughout the spectrum and provides an over-all noise reduction in this case of approximately 8 decibels.

The basic principles of muffler design for small reciprocating engines are fairly well understood and those which apply specifically to small aircraft engines are indicated in references 12 and 23. Such factors as high gas velocities and high sound pressures may cause the muffler performance to deviate somewhat from that predicted by the theory which is based on the assumption of small disturbances. For larger engines many of the basic principles may apply, but an optimum design with regard to noise reduction, weight, and safety would result only from additional research and development work.

Jet engines.- Since jet engines are prolific noise generators, there is much interest in effective muffling techniques. Consequently, a large number of governmental agencies and aircraft companies, working more or less independently, have devised satisfactory mufflers which, although differing in construction and operation, rely on the same basic principles to accomplish muffling. These mufflers are being used for ground-testing of engines mounted in test cells and for ground run-ups of production model airplanes (refs. 24 and 25). In contrast to the reciprocating-engine muffler, these designs are very large and massive and to date none is available to reduce jet noise in flight. The large size of these mufflers, as indicated in figure 16, results partly from the large volume of exhaust gases involved and partly from the presence of intense low-frequency noise components which necessitate the use of large resonant chambers in addition to the more conventional sound-absorbing materials. The outside walls are massive in order to minimize the transmission of noise generated by the high velocities and turbulence inside the muffler.

One of the basic requirements of jet muffling is that the jet exhaust first be cooled and thus reduced in velocity without building up excessive back pressures on the engine being tested. The exhaust gases are thus enclosed in a compartment in which cooling processes, such as the addition of secondary air or cooling water sprays, or both, may be applied. From the cooling chamber the exhaust gases enter the muffler at velocities of the order of 400 ft/sec. In general, satisfactory muffling results have been obtained when the jet velocity was reduced to a value of approximately 200 ft/sec or less at the muffler exit.

The principles of jet-exhaust muffling are also applicable to the air inlets of jet engines and to wind tunnels which have heat-exchange towers or openings to the atmosphere. In these latter applications the actual noise reduction would be accomplished in the same manner as in jet-exhaust muffling but, there would be no problem of cooling the exhaust gases (ref. 26).

Spatial Isolation

Since relief from noise is obtainable by merely increasing the distance between the observer and the noise source, it is of interest to evaluate this effect of distance on the noise from the various aircraft-noise sources. Noise reduction as a function of distance, in quiescent air, is shown in figure 17 for frequencies of 1000, 3000, and 10,000 cps (ref. 27). The solid line represents the noise reduction due to the normal spreading of a sound wave according to the inverse-square law. For frequencies of the order of 1000 cps or below, very little additional noise reduction due to atmospheric effects occurs, but at higher frequencies the atmospheric losses may be quite large. Since most aircraft-noise spectrums have relatively large components in the frequency range below 1500 cps, the solid line in figure 17 will essentially describe the intensity as a function of distance except for very large distances. Different results, particularly at the larger distances, may be obtained where turbulence, wind gradients, and temperature inversions are present.

The data of figure 17 are for conditions of sound propagation for clear areas such as over an airport runway and from an airplane flying overhead. In the case of terrain with obstructions such as grass, shrubbery, trees, and so forth, the average attenuation is somewhat greater than indicated in the figure.

Soundproofing

In instances where groups of people are required to be near noise sources for long periods of time, soundproofing is generally used as a means of protection. In general, this involves the use of a structure to isolate an observer from a noise source. Two physical phenomena involved in soundproofing are the sound-transmission and the sound-absorption qualities of the structure. London, in reference 28, relates these two phenomena to the reduction in intensity as a noise signal passes through the walls of an enclosure by the following expression:

$$\text{Noise reduction} = 10 \log_{10}\left(1 + \frac{\alpha}{\tau}\right)$$

where α is the absorption coefficient, τ is the transmission coefficient, and the noise reduction is given in decibels. (The absorption coefficient of a material is defined as the ratio of the sound energy which is absorbed by the material to the total energy which falls upon it. Similarly, the transmission coefficient of a given panel is the ratio of the sound energy transmitted by the panel to the total energy which impinges on it.)

Values of α and τ may vary between 0 and 1.0, depending on the noise frequency and the types and amounts of materials used in the structure. Two general conclusions may be made from a study of London's equation: (1) No noise reduction can be obtained unless there is some absorption ($\alpha > 0$) and (2) the values of τ must be small in order to realize large noise reductions. Data are presented in references 28 and 29 which indicate that nominal values of the absorption coefficient ($\alpha = 0.20$ to 0.50) are easily obtainable for a variety of sound treatments in the range of speech frequencies at least. In accomplishing large noise reductions where small values of τ and at least nominal values of α are needed, the transmission properties of the structure may therefore be of primary importance.

Figure 18 shows the theoretical transmission loss as a function of frequency for sound passing through three homogeneous panels differing in surface density. The value of 1 lb/ft^2 may be considered representative of airplane-fuselage construction; whereas the value of 100 lb/ft^2 is more of the order of test-cell construction. Although some variations in the data exist, the trends in figure 18 have been verified by experiment (ref. 30). In general the larger losses are seen to occur at the higher frequencies and relatively small losses at the lower frequencies. In order to increase the transmission losses at the lower frequencies, the weight of the structure must be increased. The values in figure 18 correspond to conditions of perfect absorption ($\alpha = 1.0$) and hence are generally larger than would be obtained in practice.

Figure 19 shows the relative amounts of noise reduction obtainable at various frequencies by the addition of absorbing material such as glass wool, trim cloth, carpeting, and so forth, to an airplane fuselage compared with that obtained with the bare fuselage (ref. 31). For the range of frequencies of speech fairly large noise reductions are obtainable by the use of relatively light weight absorbing materials. For the lower frequencies, however, this conventional method of airplane sound treatment provides rather small amounts of noise reduction.

In general, figures 18 and 19 indicate that noise reductions are much more easily obtained at the higher frequencies than at the lower ones. This finding is significant since in figures 4, 5, and 6 aircraft-noise spectrums are shown to contain relatively intense low-frequency components. Substantial reductions at the very low frequencies may require massive structures or the use of special techniques, or both. Of special interest in this regard is the use of some unique methods in the sound treatment of a large wind tunnel (ref. 26).

Personal Protection

The most widely used type of personal protection for persons working close to the noise source is the earplug. This device in combination with the ear muff provided in the standard Air Force type helmet provides substantial noise reduction over a wide range of frequencies. The effectiveness, separately and in combination, of typical earplugs and helmets under optimum conditions is shown in figure 20, in which the noise attenuation is plotted as a function of frequency (ref. 32). The attenuation available for a combination may vary from approximately 30 to 80 decibels, depending on the noise frequency, and for the speech range averages approximately 50 decibels.

The difference in level between air conduction and bone conduction of sound is approximately 50 decibels. Equipment designed for protection against bone conduction would be very cumbersome and hence of limited use. The protection provided by a well-fitted earplug and helmet combination may therefore represent the practical limit of protection for the ear. This combination will provide adequate protection for relatively short exposures to levels up to approximately 145 decibels or for long-term exposures to nominal intensity levels. Intensity levels of this order of magnitude are uncomfortable to the observer because of effects on other parts of the body unless some protection is provided. Since personal protection from the intense low frequencies which are felt by the body as a whole would also be too cumbersome, soundproofing or spatial isolation may be the best solution.

CONCLUDING REMARKS

This brief survey has been aimed at providing a background for the understanding of interrelated noise questions. Some of the effects of noise have been pointed out briefly as background information for the reader, and some physical characteristics of aircraft noise as well as some means of protection from noise have also been briefly discussed.

These and other related studies indicate that no easy and inexpensive solution to the aircraft-noise problem is available at present. Reductions of noise at the source are possible in some cases, as for the propeller and the reciprocating engine, but only if a possible performance penalty is acceptable. The problem of providing adequate protection is in many cases expensive and is complicated by the intense low-frequency content of the noise from most aircraft-noise sources.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., March 12, 1952

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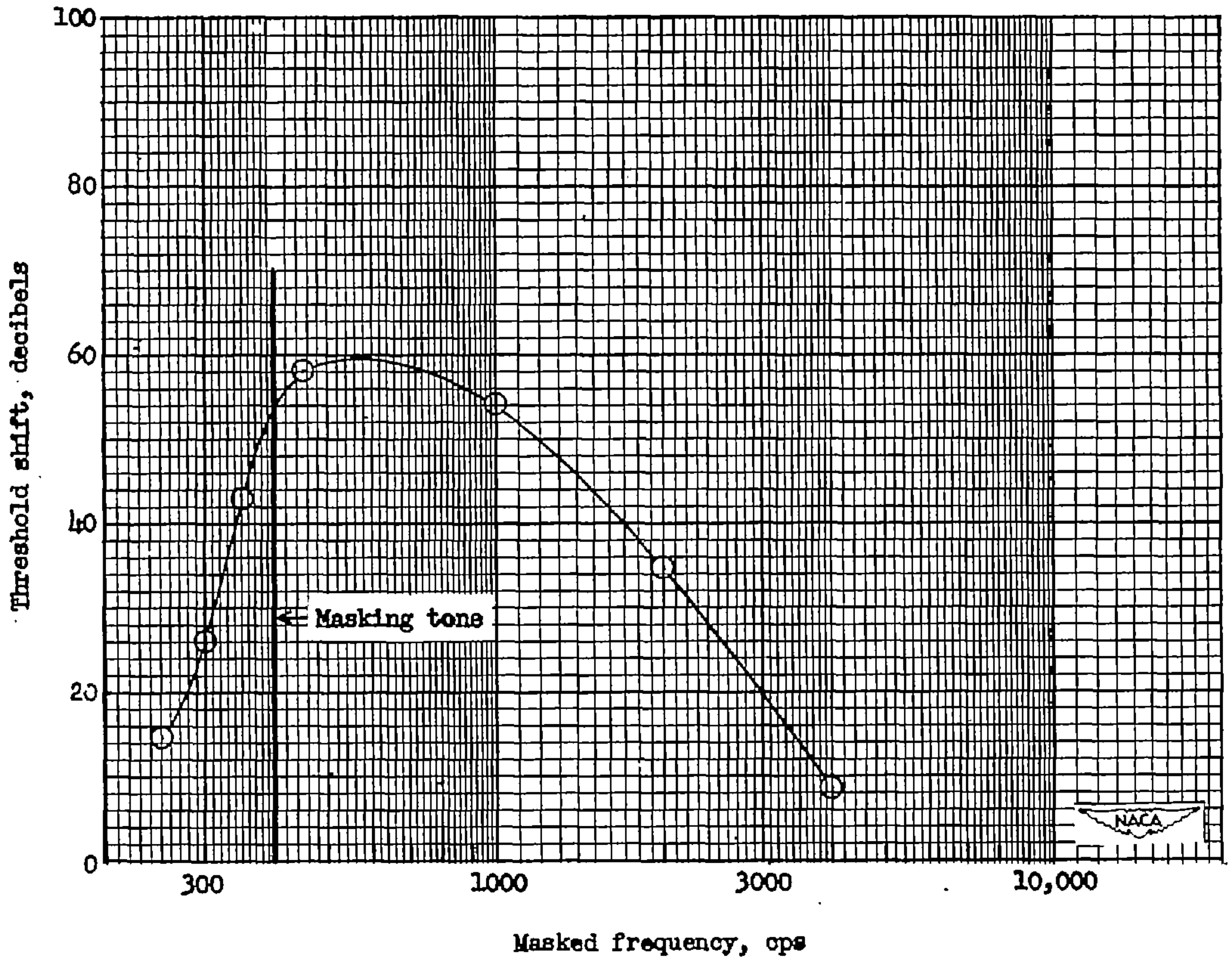


Figure 1.- Threshold shift as a function of frequency for a 400-cps tone of 70 decibels. (Data obtained from ref. 2.)

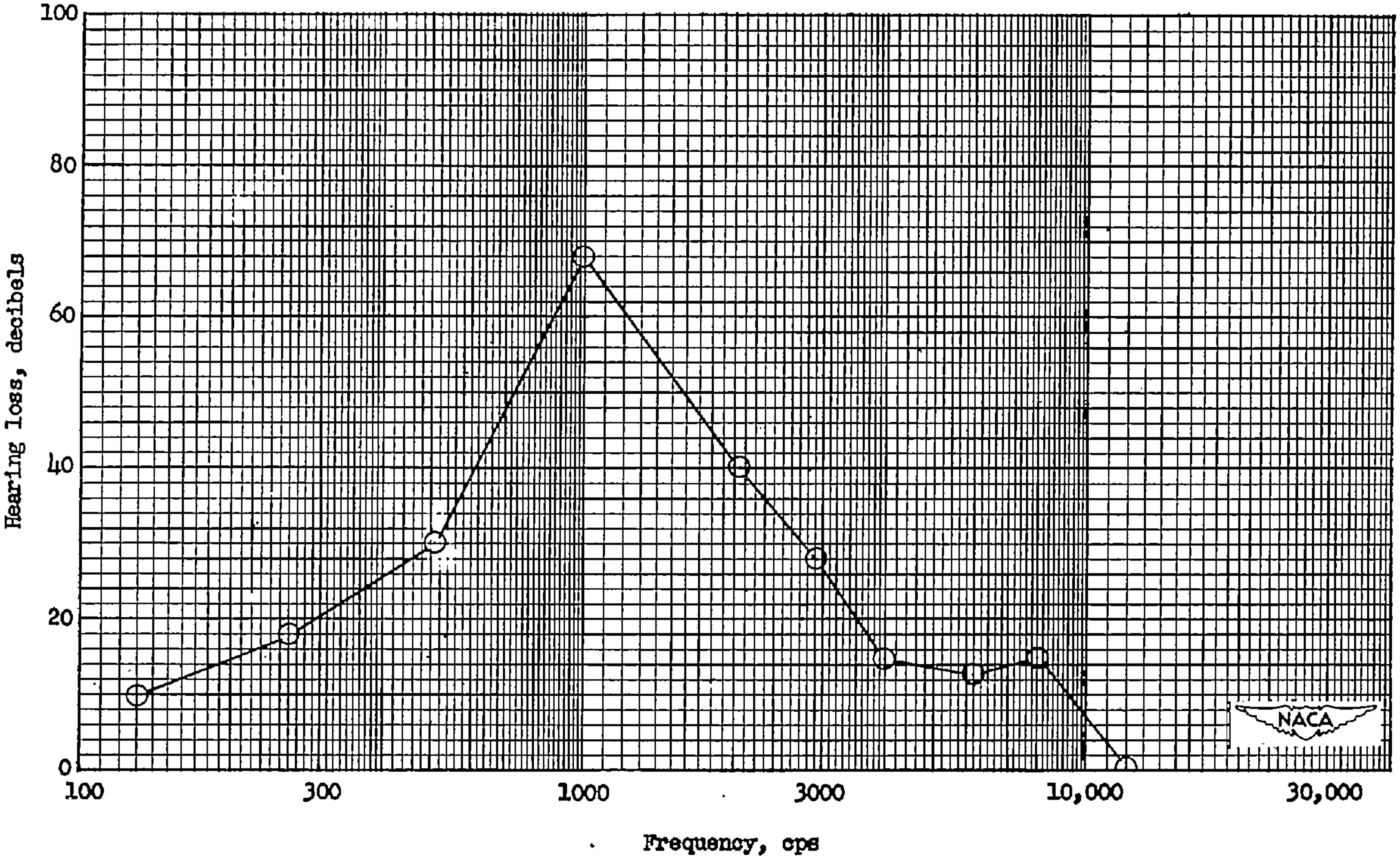


Figure 2.- Temporary hearing loss as a function of frequency for an unprotected observer following a 10-minute exposure to jet-engine noise of 146 decibels. (Data obtained from ref. 5.)

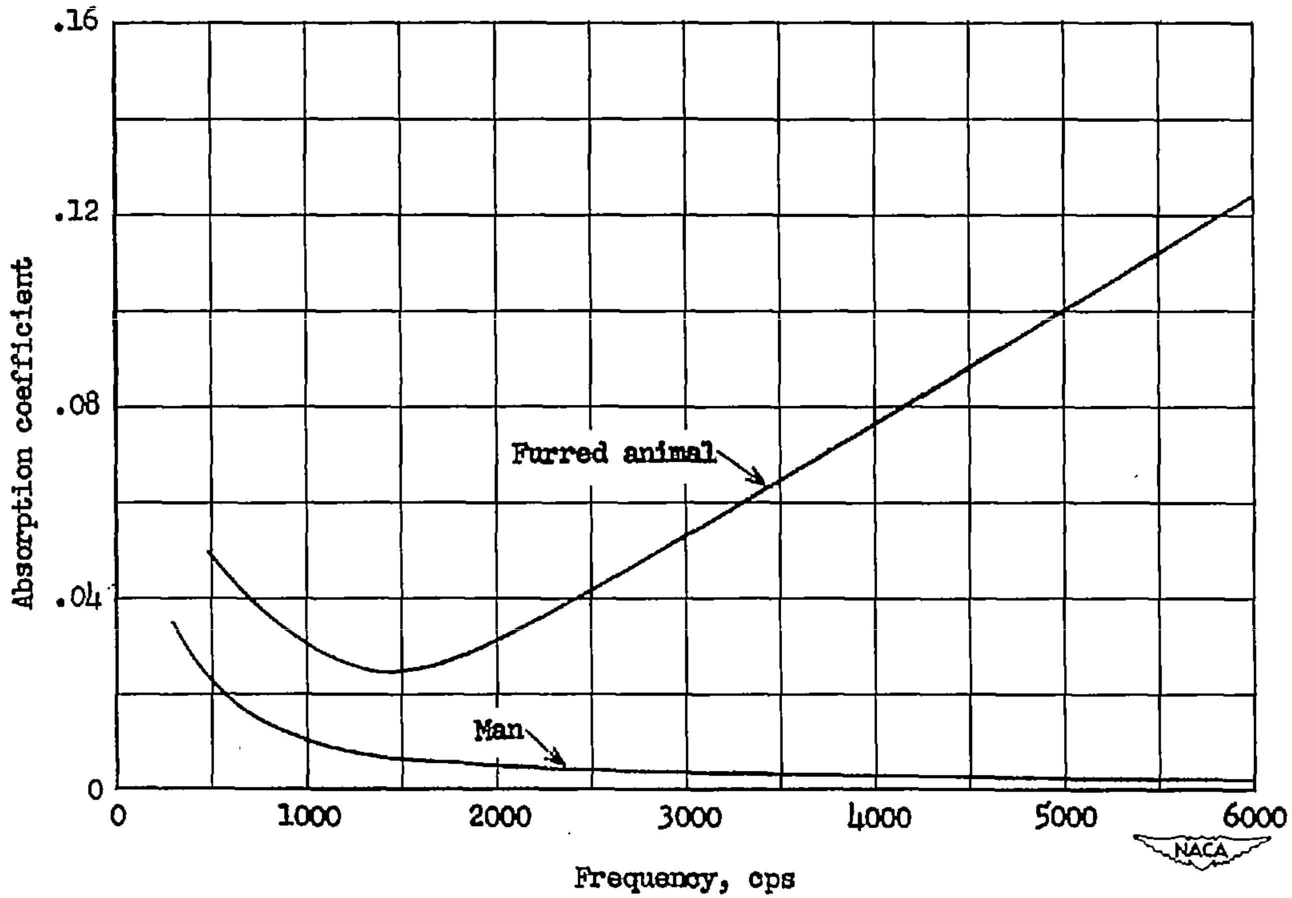
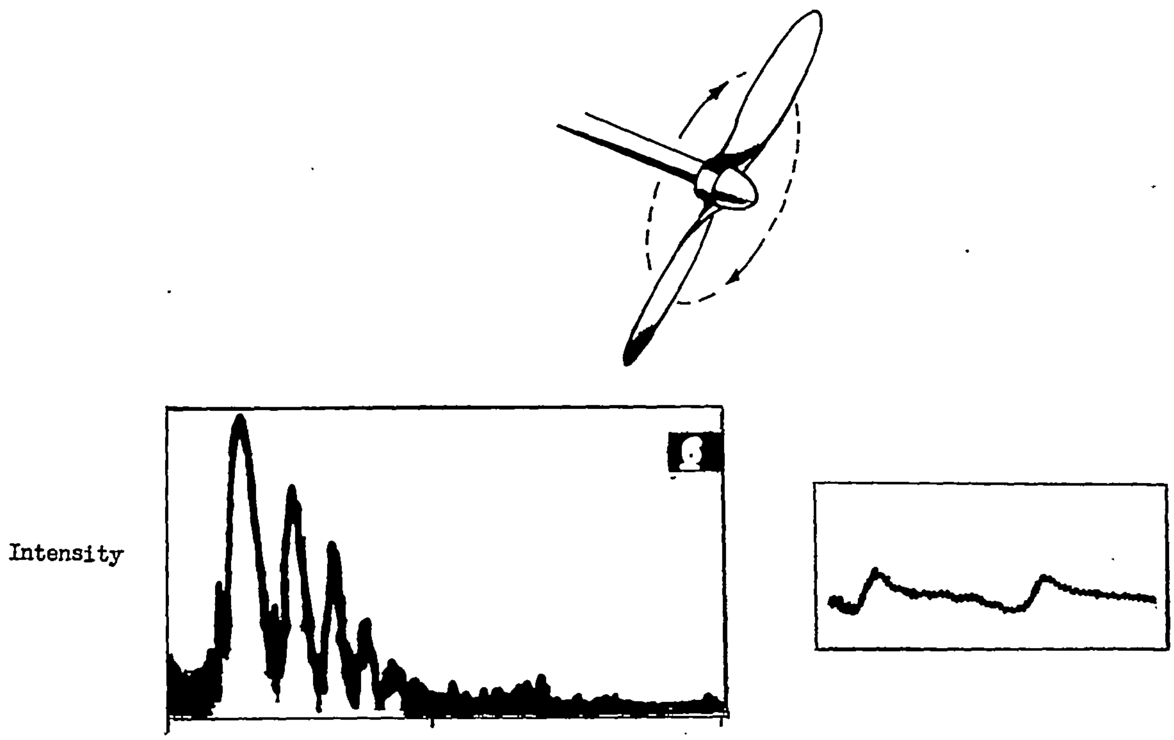
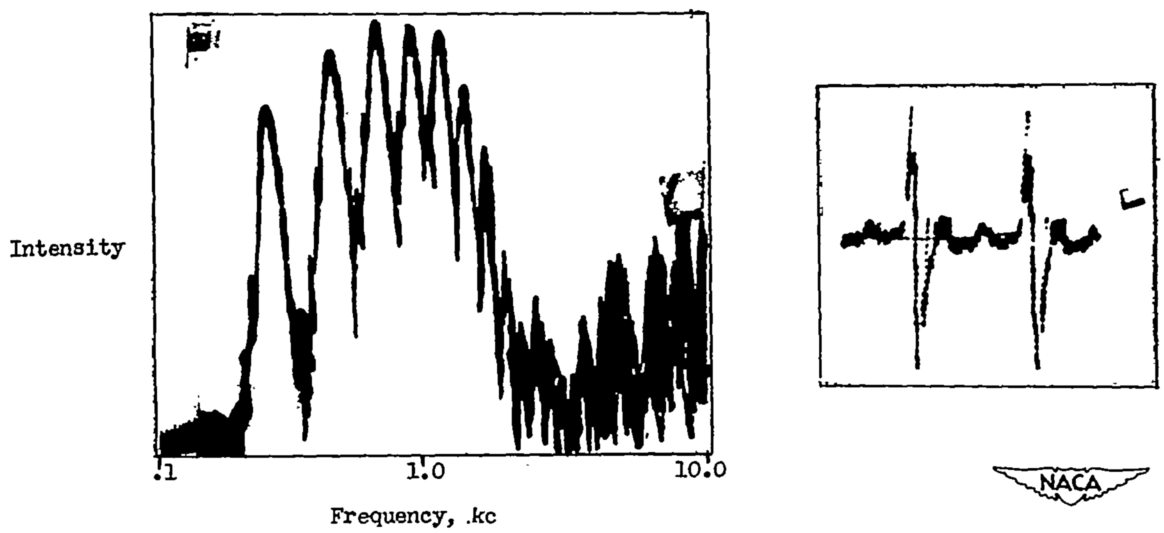


Figure 3.- Absorption coefficients as a function of frequency for a furred animal as compared to those of man. (Data obtained from refs. 7 and 8.)



(a) Subsonic tip speed.



(b) Supersonic tip speed.

Figure 4.- Noise generated by propellers.

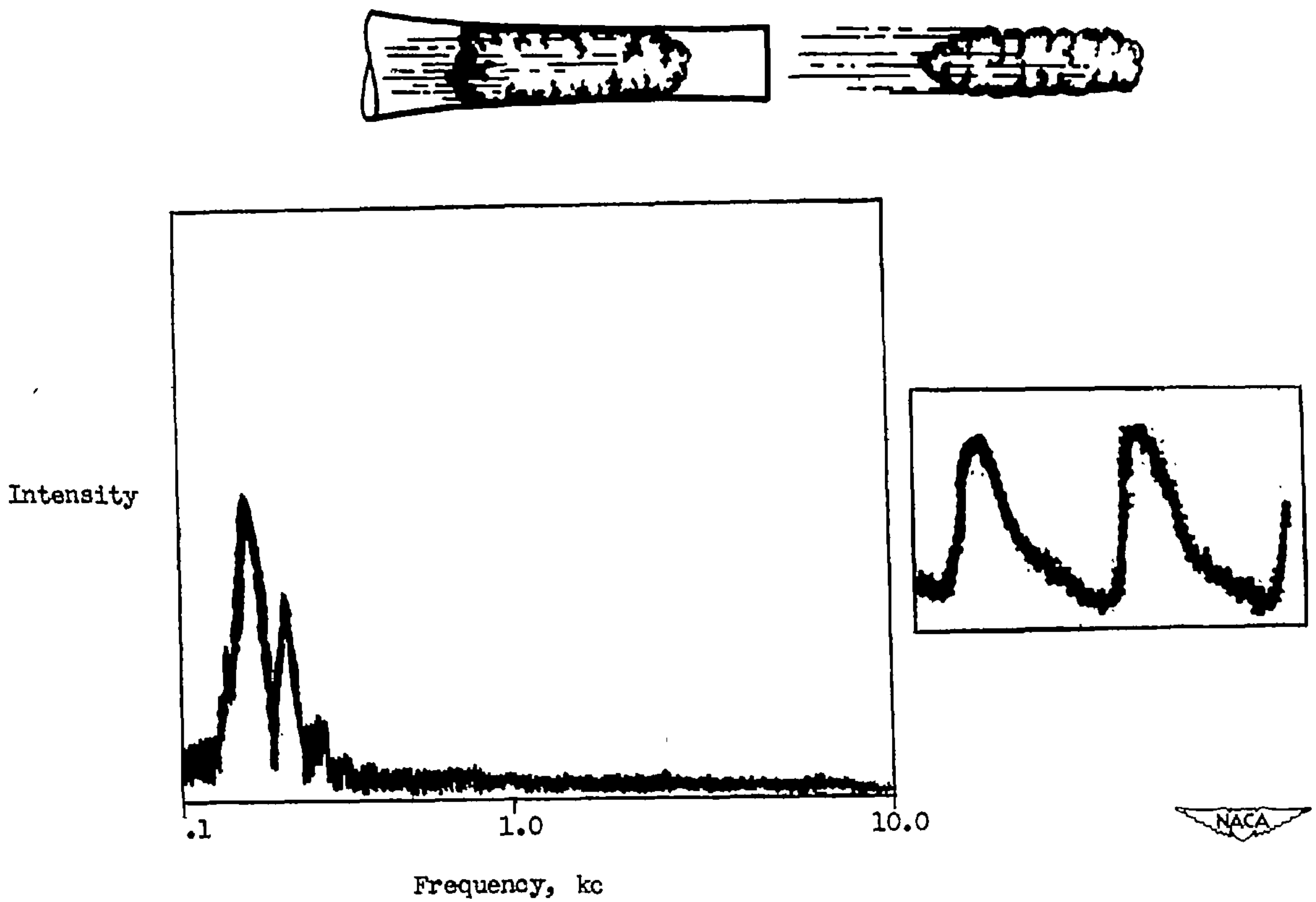


Figure 5.- Noise generated by a pulsing flow.

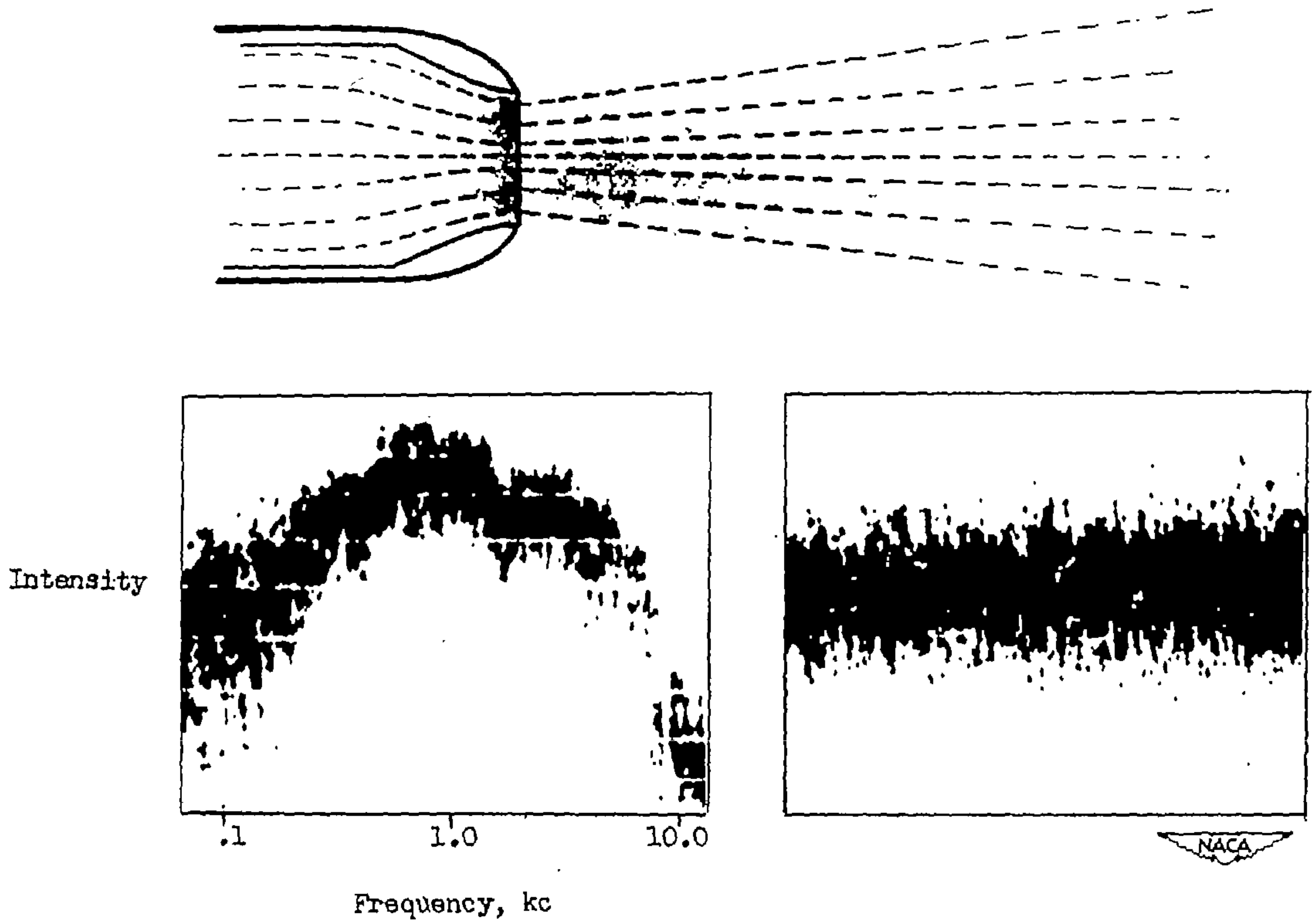


Figure 6.- Noise generated by jet mixing and turbulence.

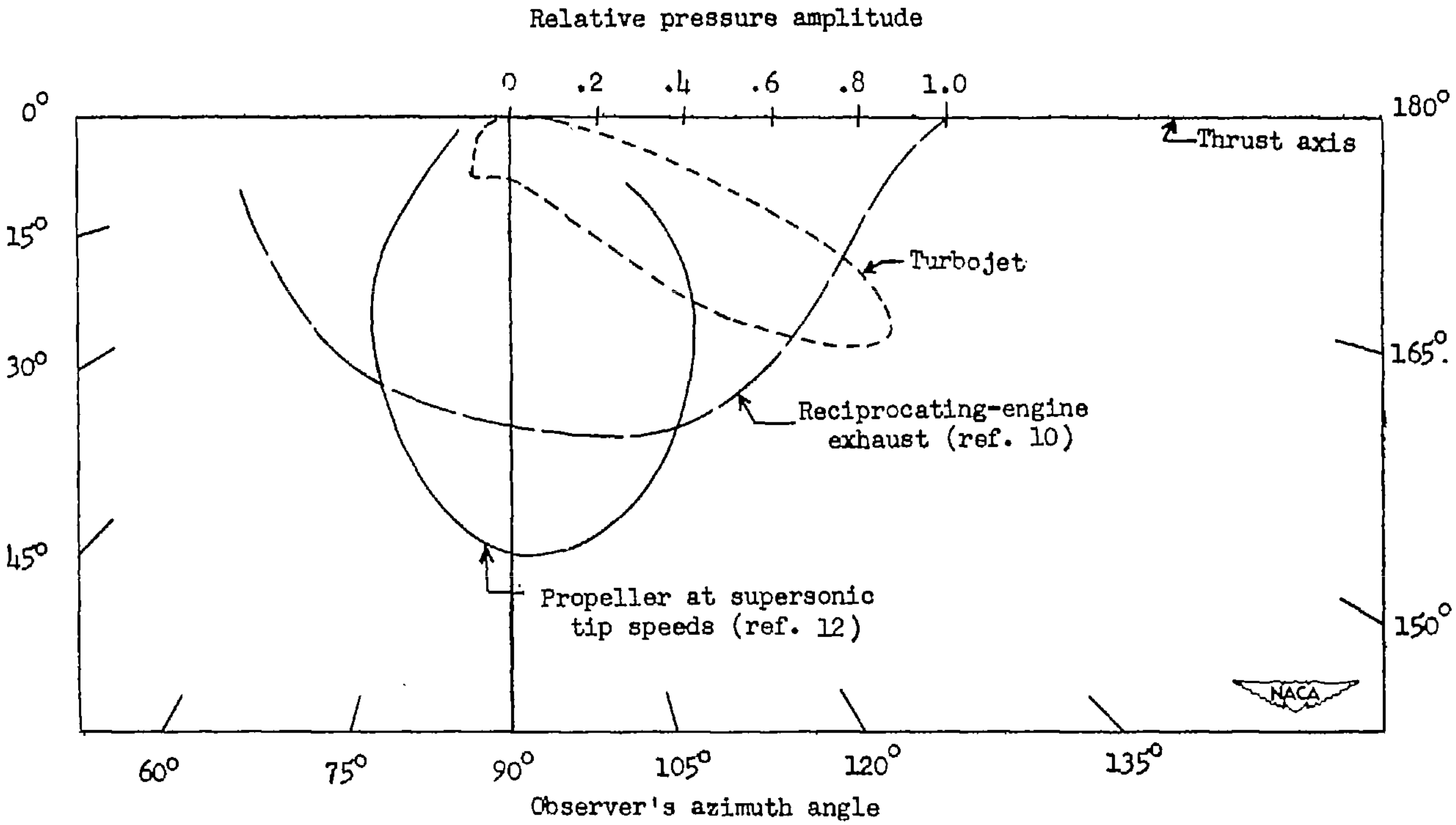


Figure 7.- Directional characteristics of the noise generated by three different types of aircraft-noise sources. (Data have been adjusted to equal maximum values for comparison.)

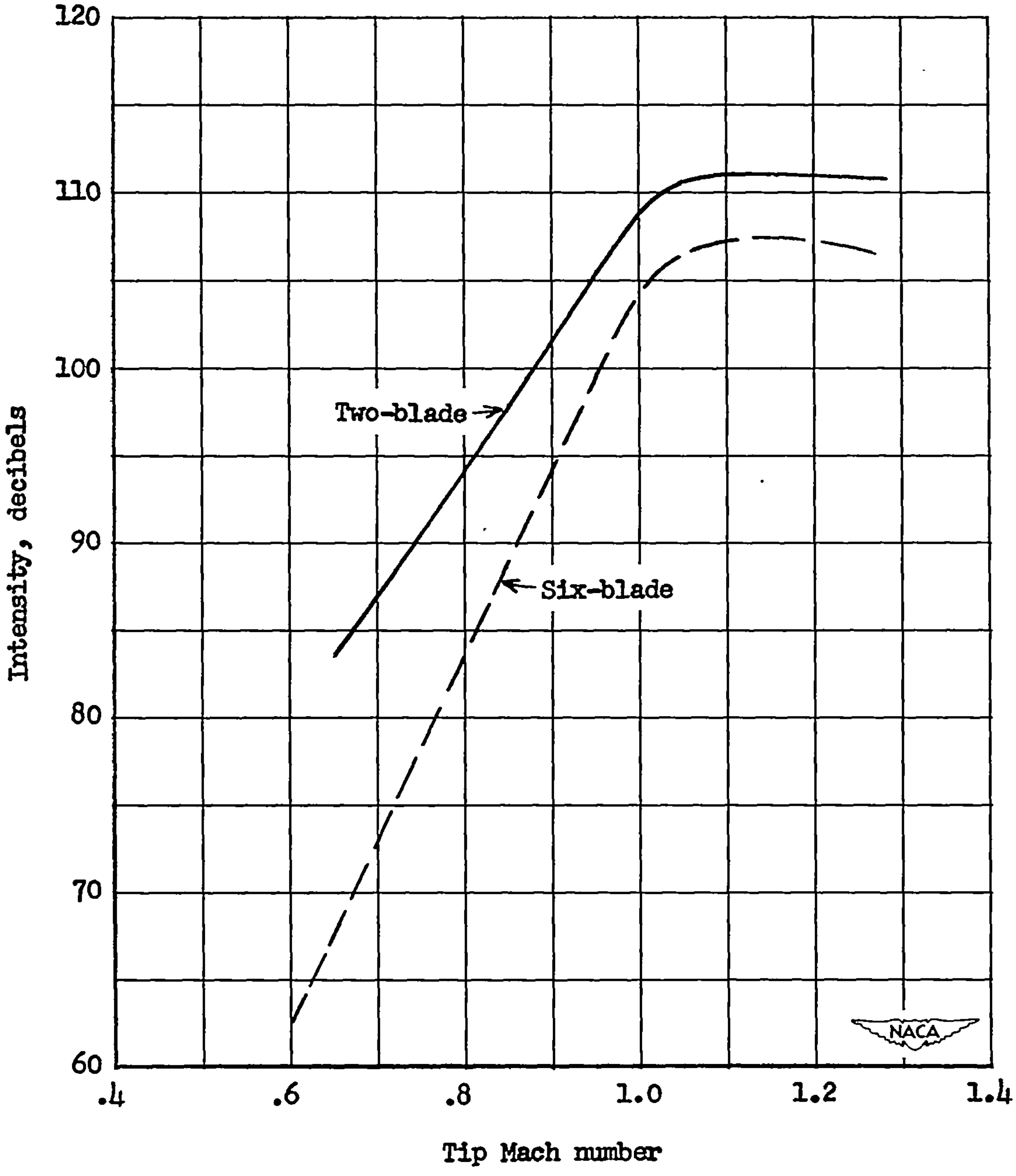


Figure 8.- Effects of tip Mach number and number of blades on the noise produced by single-rotating propellers at constant power input.

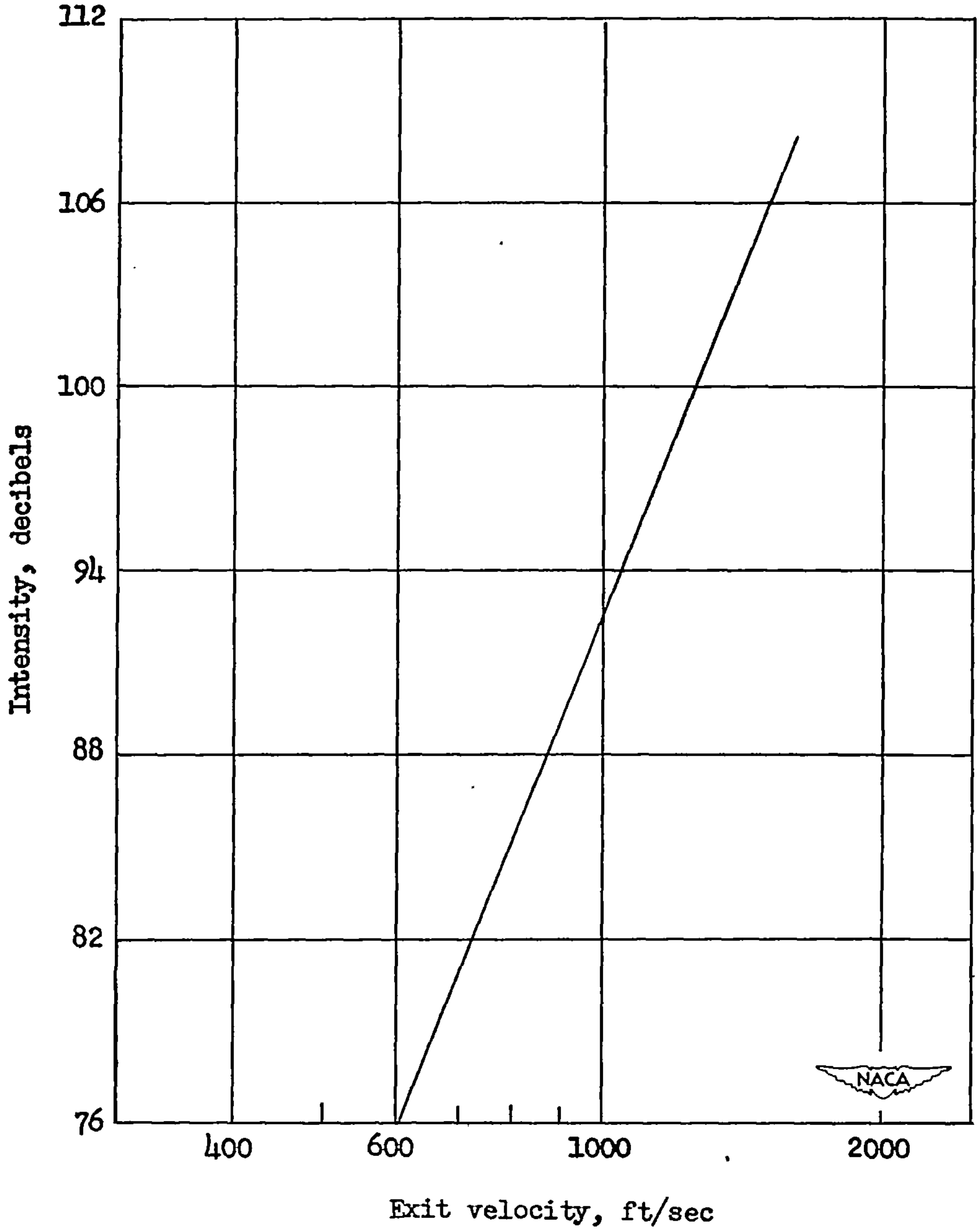


Figure 9.- Turbojet-engine noise as a function of the exit gas velocity. (Data correspond to a distance of 300 feet at an angle of 90° relative to the jet axis.)

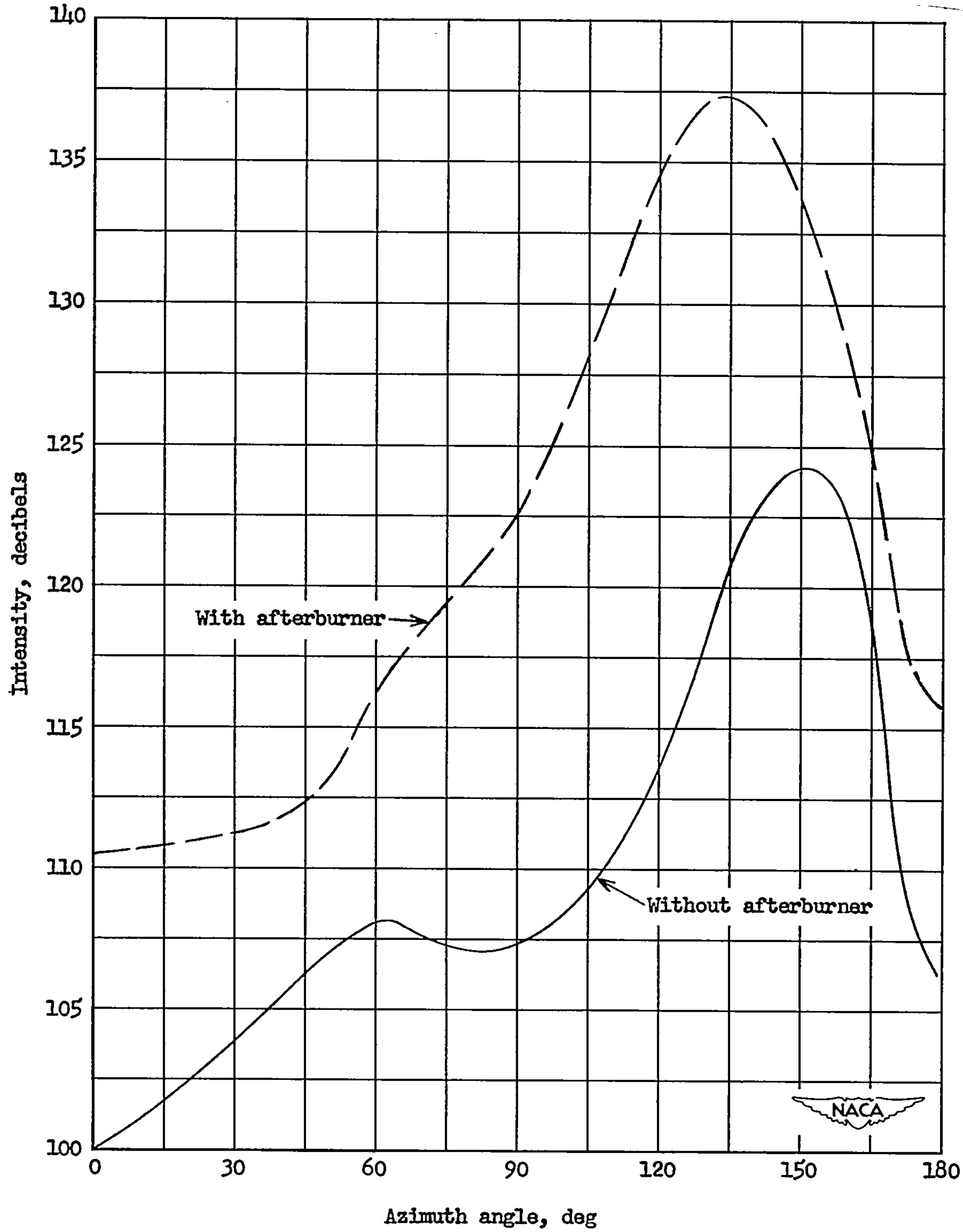


Figure 10.- Comparison of the over-all intensity levels at various azimuth angles for a turbojet engine with and without afterburner. (Data correspond to conditions of 5000 pounds of thrust and a distance of 300 feet.)

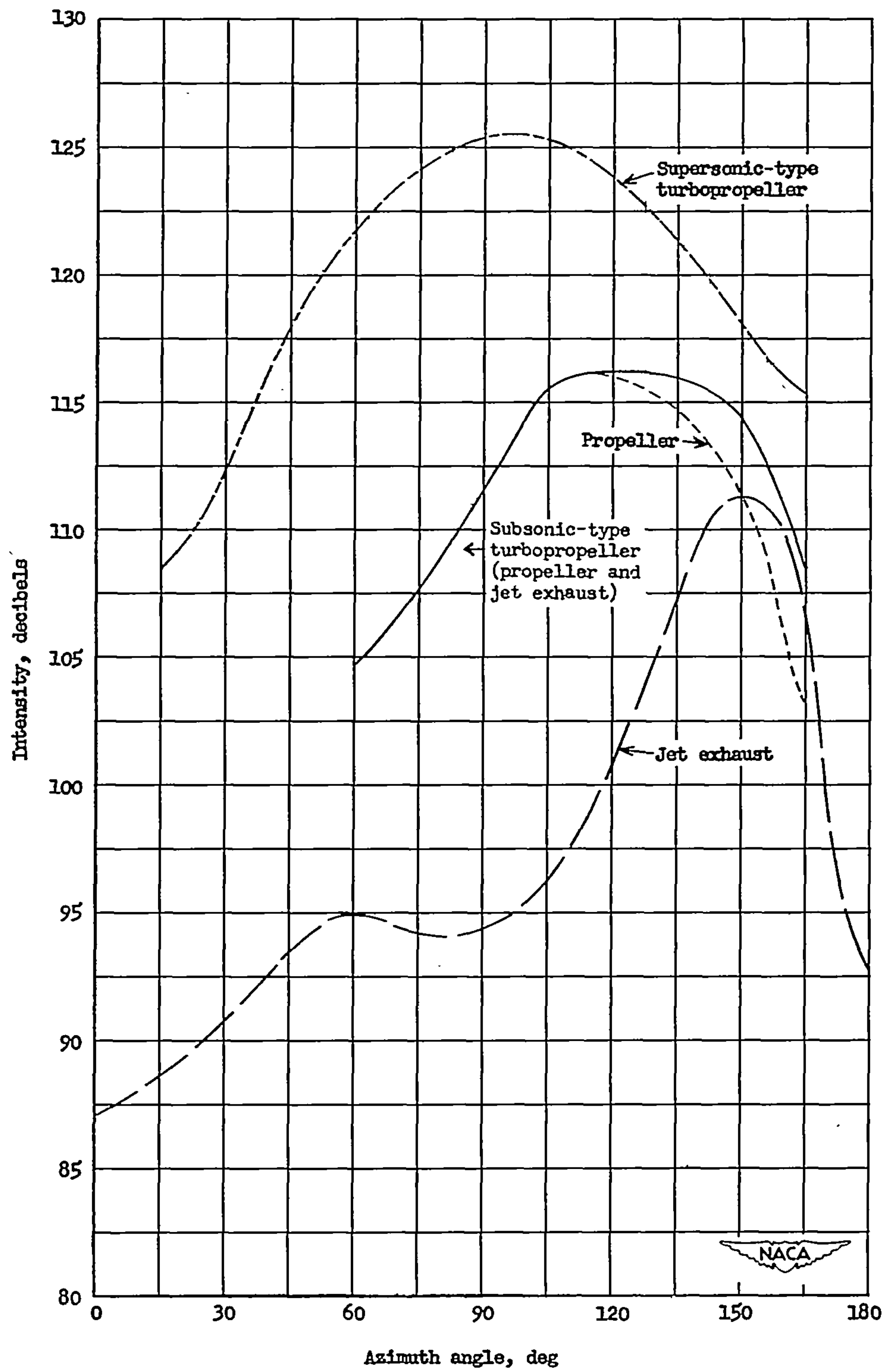


Figure 11.- Estimated intensity levels as a function of azimuth angle for two turbopropeller units. (Data have been adjusted to correspond to 5000 pounds of thrust and a distance of 300 feet.)

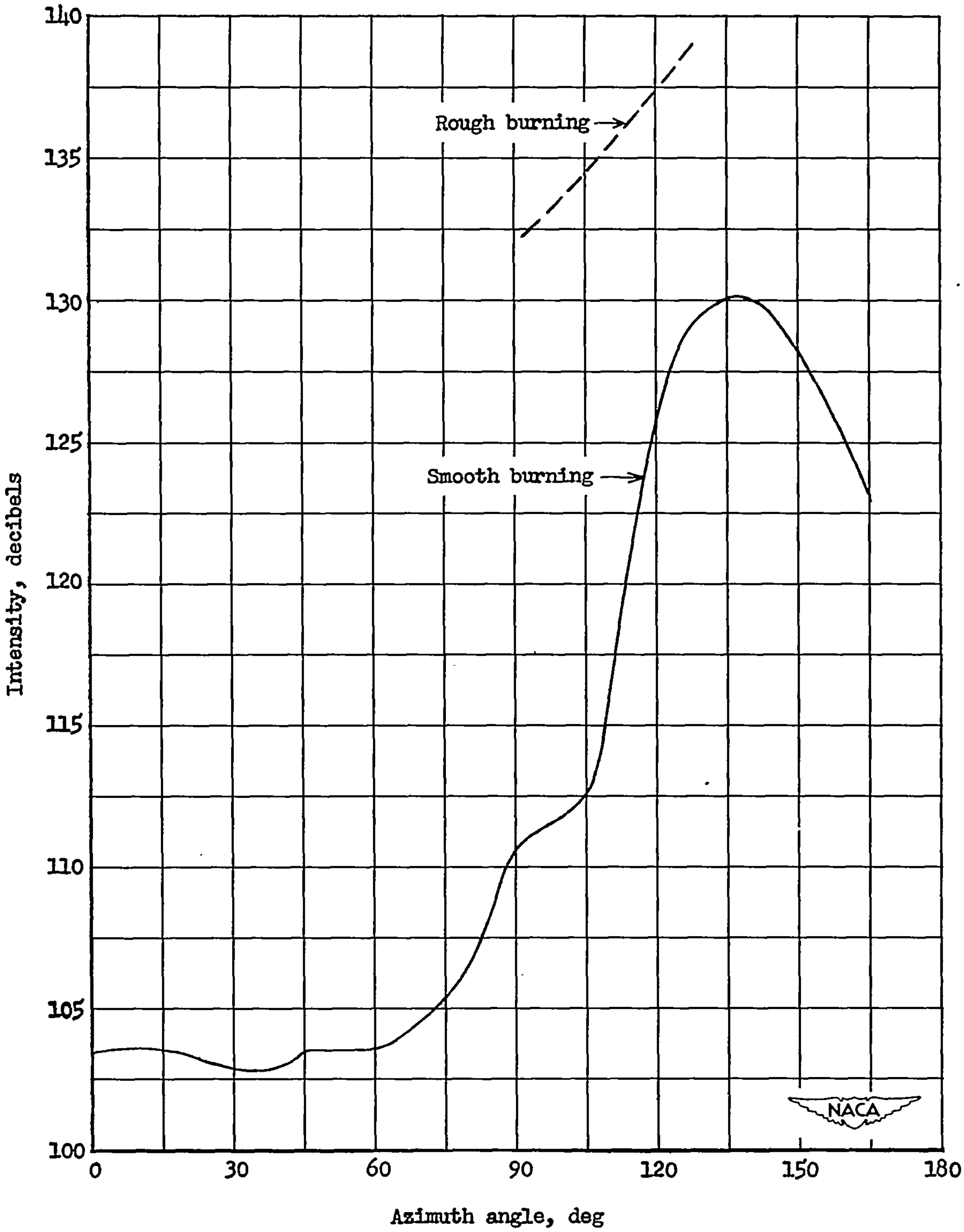


Figure 12.- Intensity level as a function of azimuth angle for two solid-fuel rocket engines. (Data have been adjusted to correspond to 5000 pounds of thrust and a distance of 300 feet.)

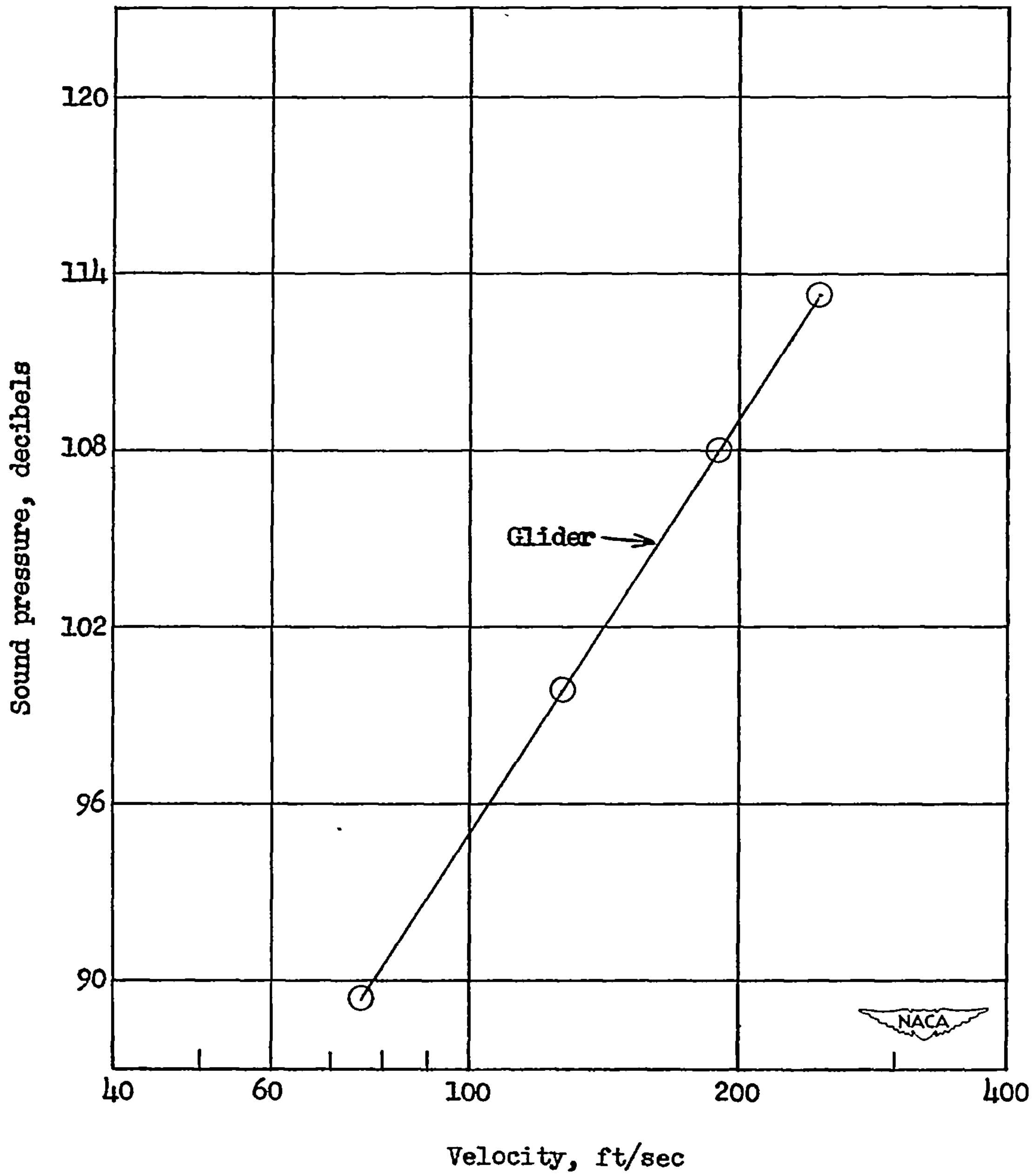


Figure 13.- Aerodynamic noise in a large glider as a function of airspeed. (Data obtained from ref. 22.)

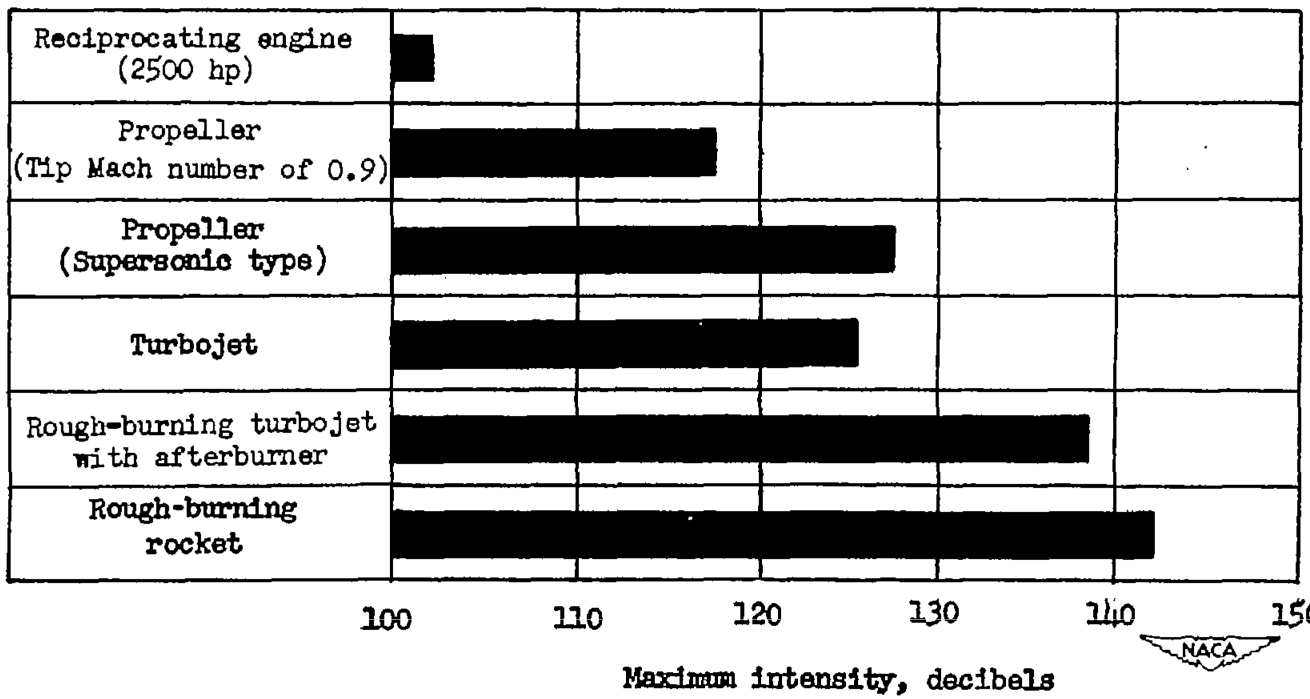


Figure 14.- Comparison of the maximum over-all intensity levels generated by various propulsive units. (Data correspond approximately to a thrust of 5000 pounds and a distance of 300 feet.)

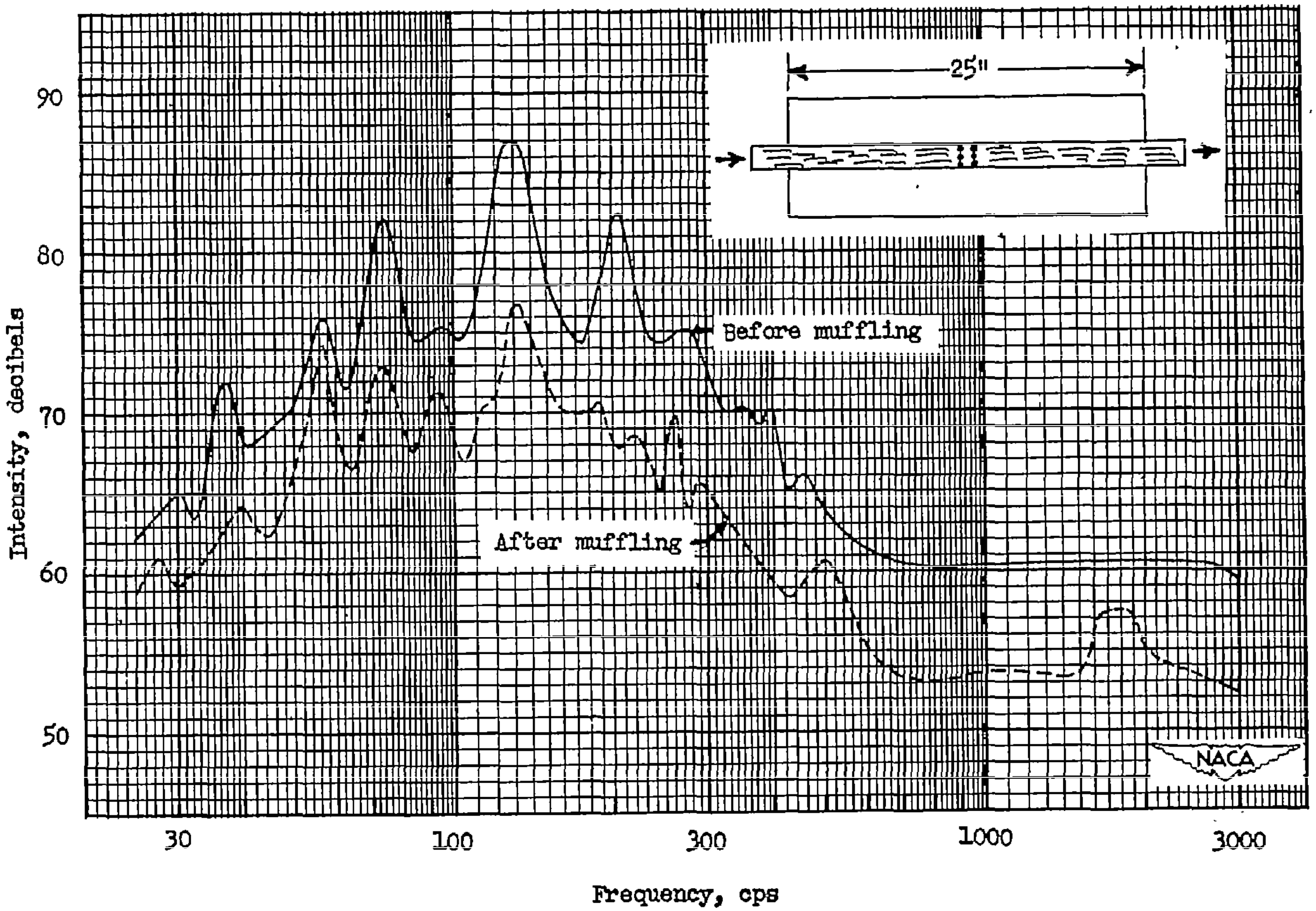


Figure 15.- Exhaust noise spectrums for a small reciprocating engine before and after muffling.

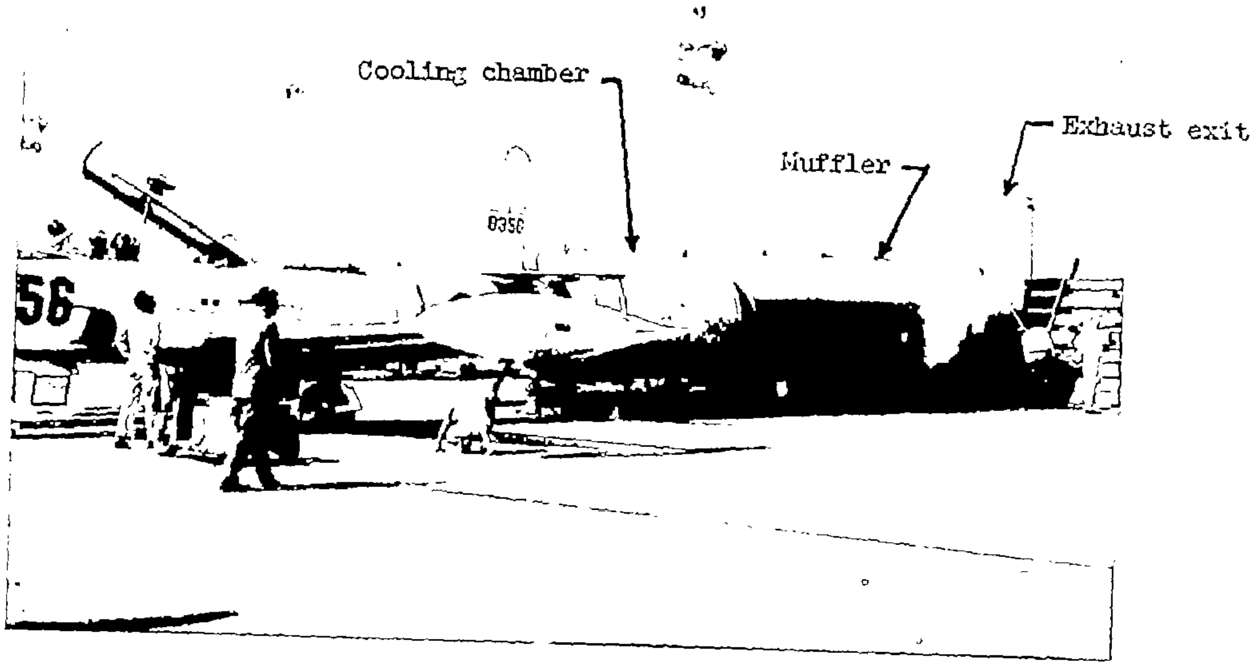


Figure 16.- Maxim silencer used by the Lockheed Aircraft Corp. for exhaust-noise reduction in the ground-testing of jet aircraft. (Photograph is reproduced by courtesy of the Maxim Silencer Co. of Hartford, Conn.) L-74372

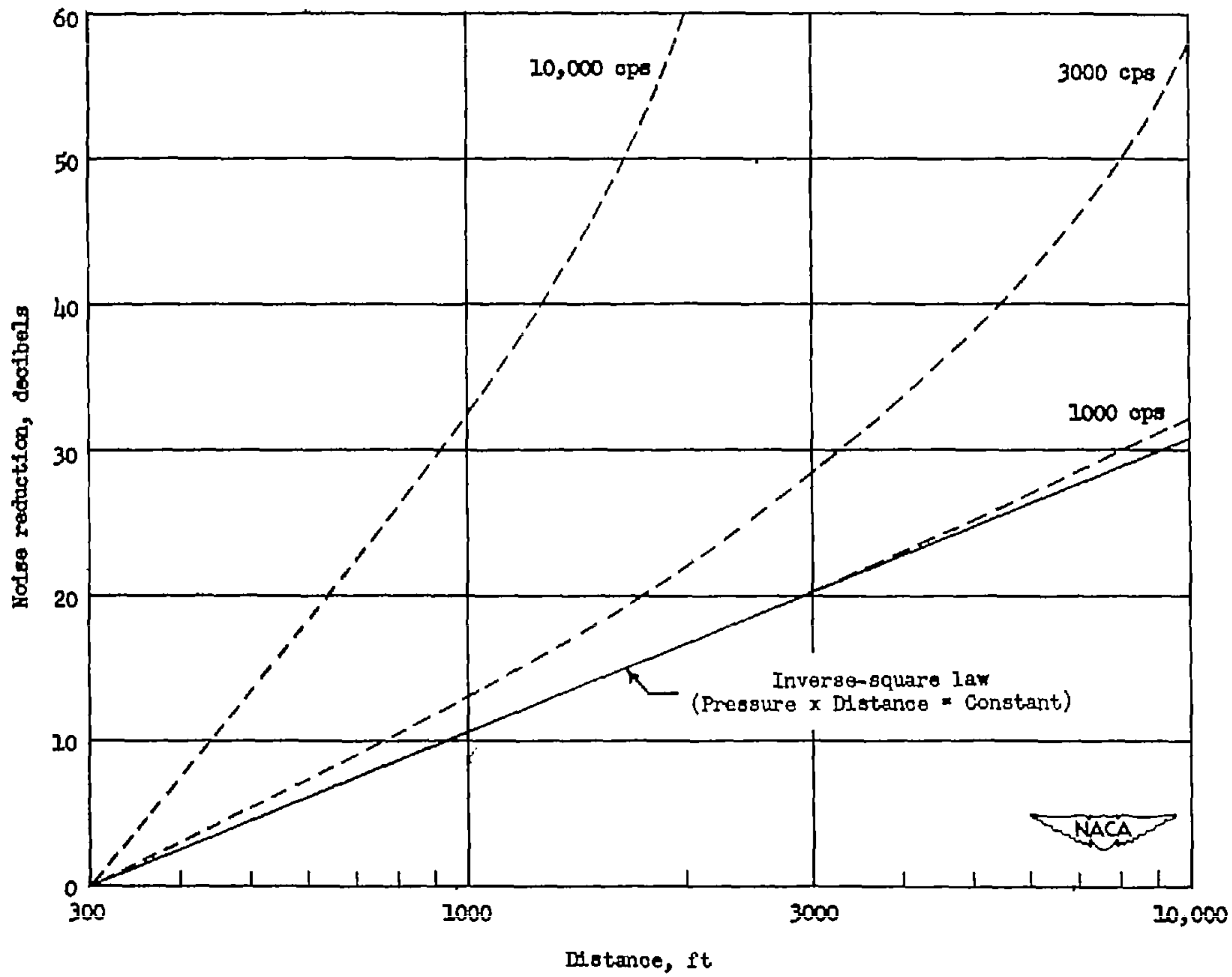


Figure 17.- Noise reduction as a function of distance from the source for three different frequencies. (Data obtained from ref. 27.)

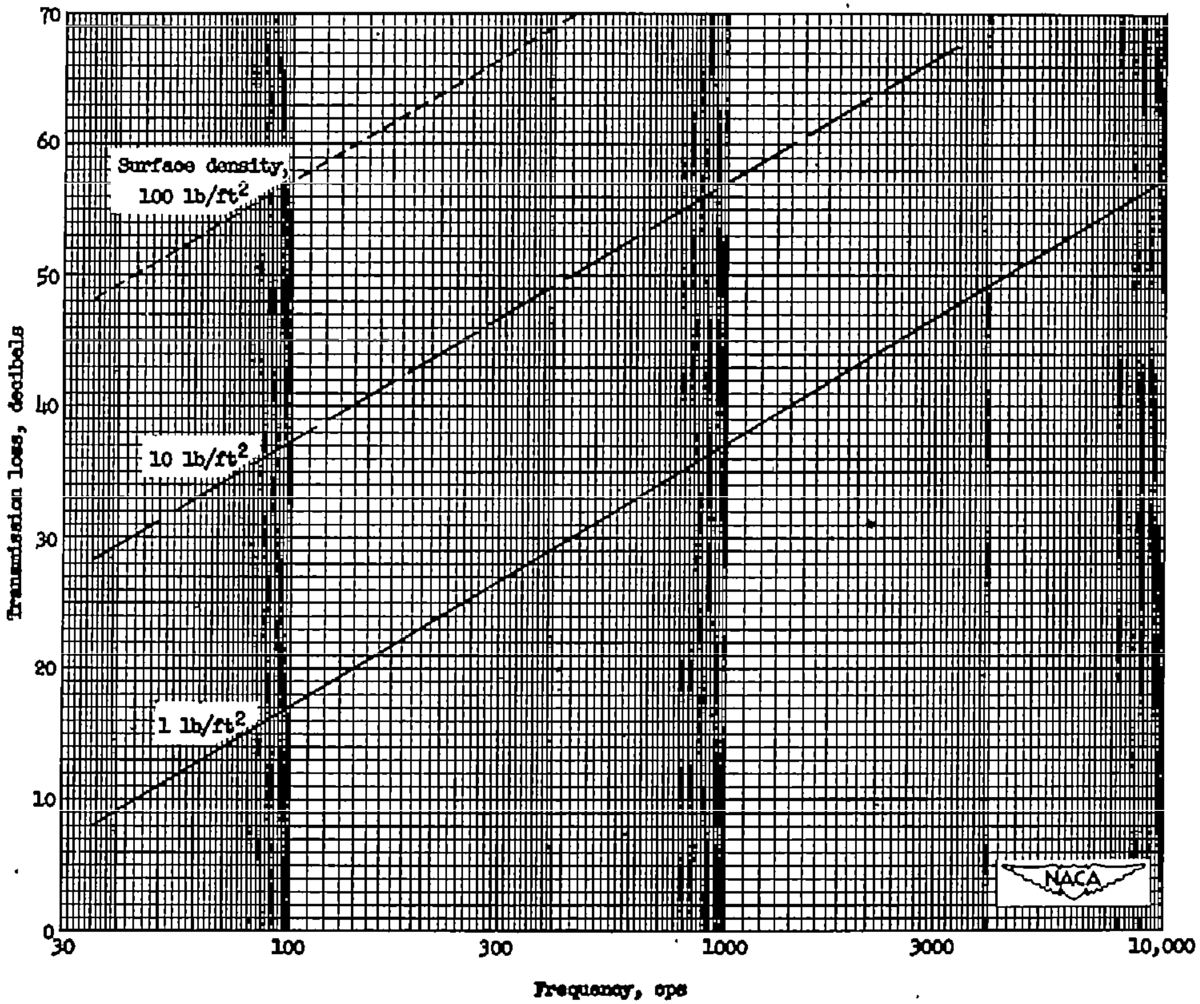


Figure 18.- Theoretical transmission loss as a function of frequency for three homogeneous panels varying in surface density. (These data correspond to conditions of perfect absorption.)

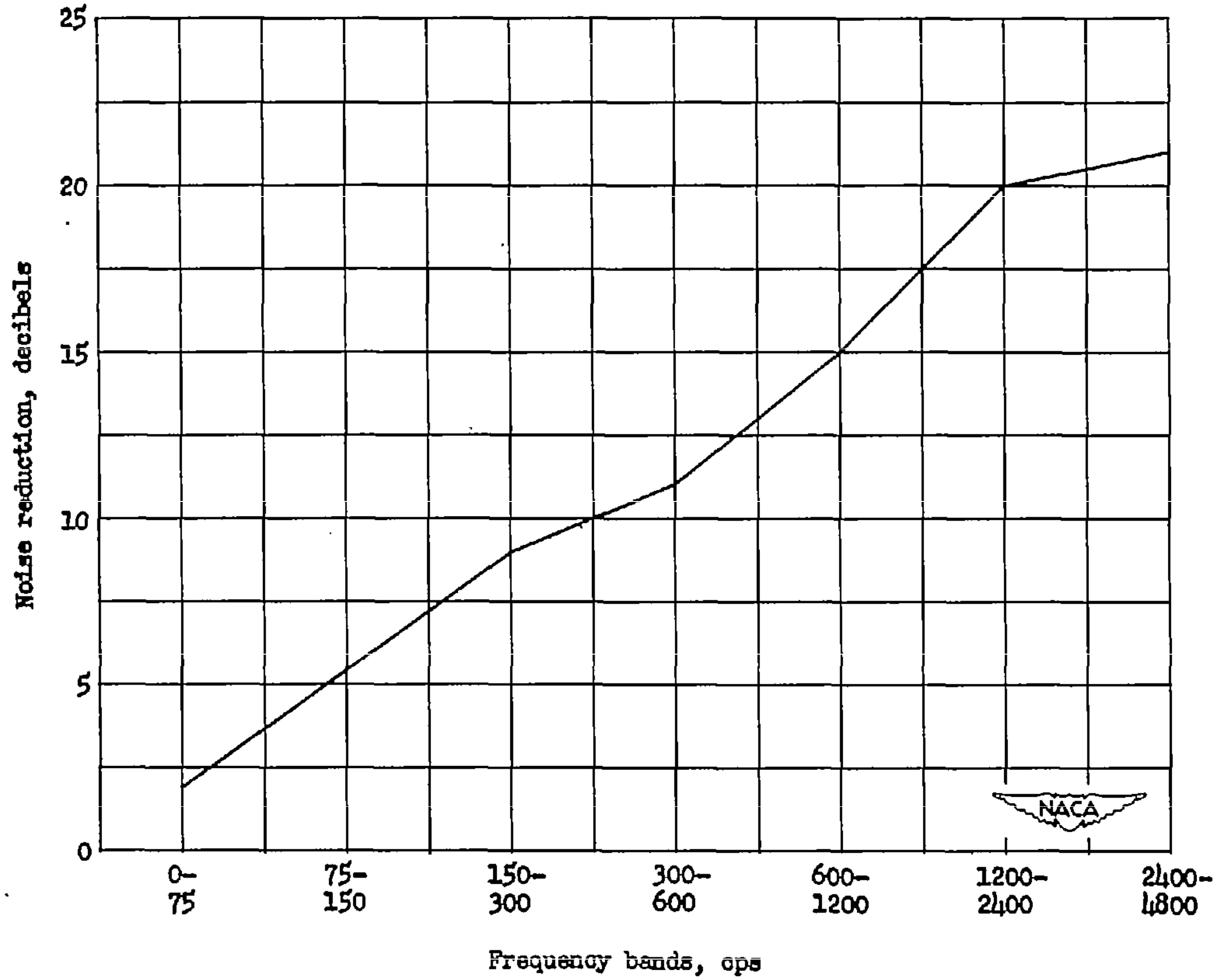


Figure 19.- Noise reduction obtainable for various frequency bands in an airplane fuselage by conventional soundproofing techniques. (Data obtained from ref. 31.)

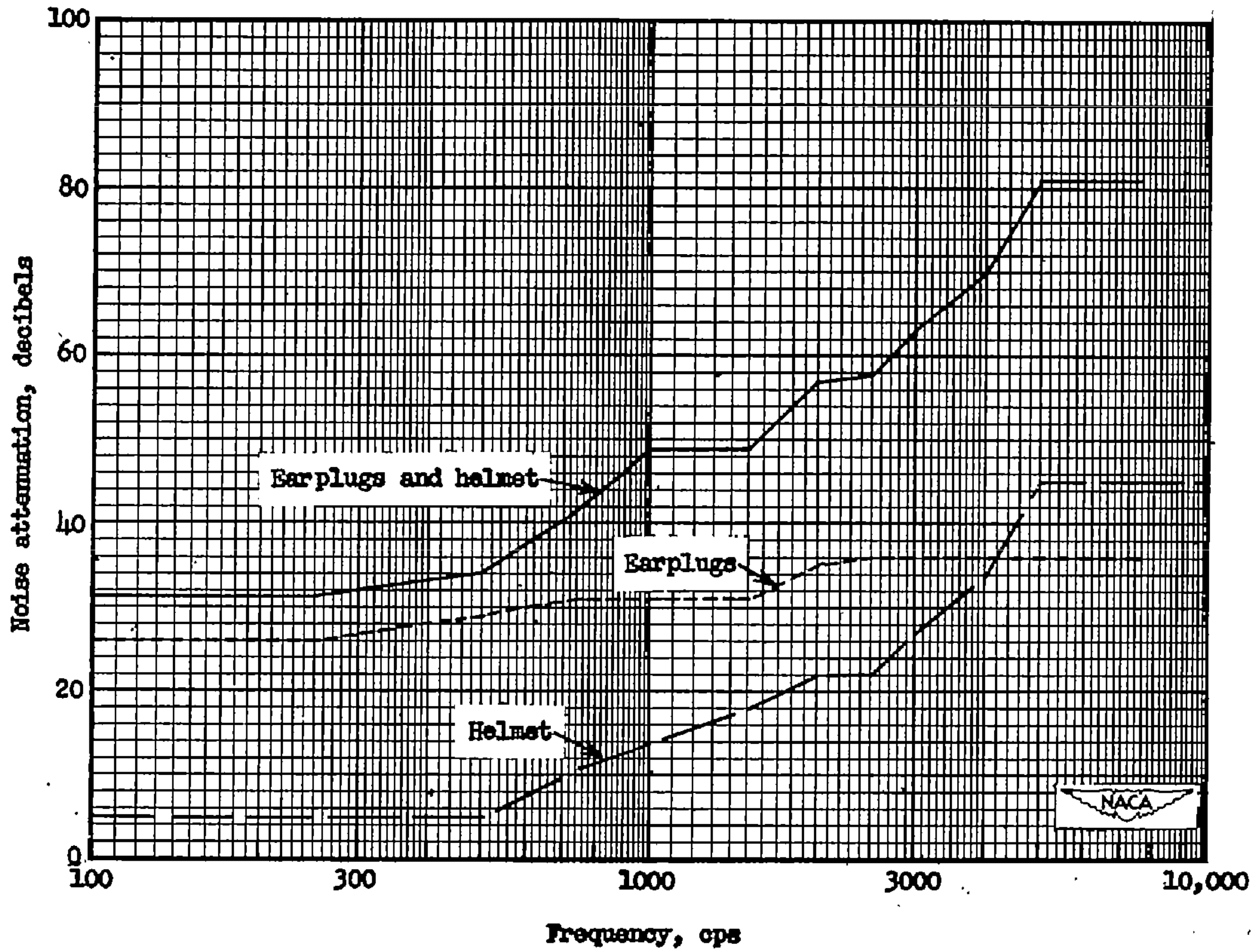


Figure 20.- Noise attenuation as a function of frequency for V-51R earplugs and the Air Force type helmet under optimum conditions of fit. (Data obtained from ref. 32.)